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THEORETICAL AND PRACTICAL ELECTRICAL ENGINEERING

COMPRISING A COURSE OF LECTURES GIVEN AT THE BLISS ELECTRICAL SCHOOL UPON THE PRINCIPLES AND APPLICATIONS OF BOTH DIRECT AND ALTERNATING CURRENT APPARATUS

By
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VOLUME II

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TRANSFORMERS

INDUCTION COILS

The discovery of electro-magnetic induction was due to Michael Faraday, in 1831. After finding that a voltage could be induced in a closed circuit by moving a magnet in its vicinity, he followed up this discovery by ascertaining that a current whose strength is changing may induce a secondary voltage in a closed circuit near it. If a coil of wire is placed parallel to another coil, the variation of a current in one will bring about the induction of an e.m.f. in the other. This is called **mutual induction.** Coils operating upon this principle are employed for medical work, where they are called **Faradic coils** in honor of

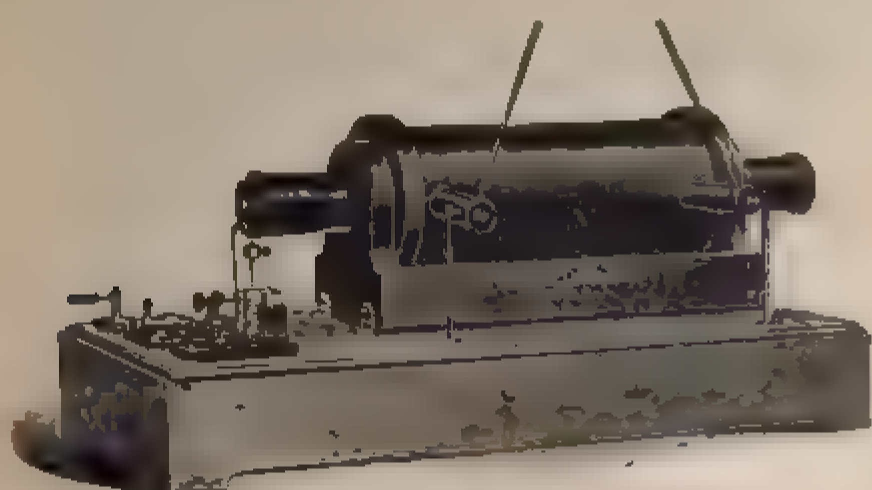


Fig. 674. Induction coil with Leed's multiple-independent vibrator.

Faraday. Coils of larger size are designed to excite X-ray tubes or for the transmission of radio signals, etc. The general appearance of a simple induction coil is shown in Fig. 674. The circuits through the coil are given in Fig. 675. Here current from a battery *B* is led through the primary winding, *P*, surrounding an iron core, *C*, and the circuit, which is completed through some form of interrupter, *V*, leads to the battery via the switch *S'*. Surrounding the primary winding is the secondary winding, *S*. When the circuit is completed the current rises in the primary winding and the magnetic flux through the core accompanies its rise. This induces an e.m.f. in the secondary winding. When the circuit is interrupted, the lines of force

collapse on the secondary, cutting it in the reverse direction, thereby inducing an e.m.f. in the reverse direction. The core is generally constructed of a bundle of soft iron wires varying from ¼ to 1½ inches in diameter and from 4 to 18 inches in length. The core is laminated to prevent the circulation of eddy currents for the same reason that the core of the armature of a generator is laminated. The primary winding consists of either two or four layers of wire varying in size from as small as No. 18 in induction coils for telephone work to as large as No. 8 for coils producing a spark 12 to 15 inches in length. The secondary winding usually consists of No. 36 wire. The amount

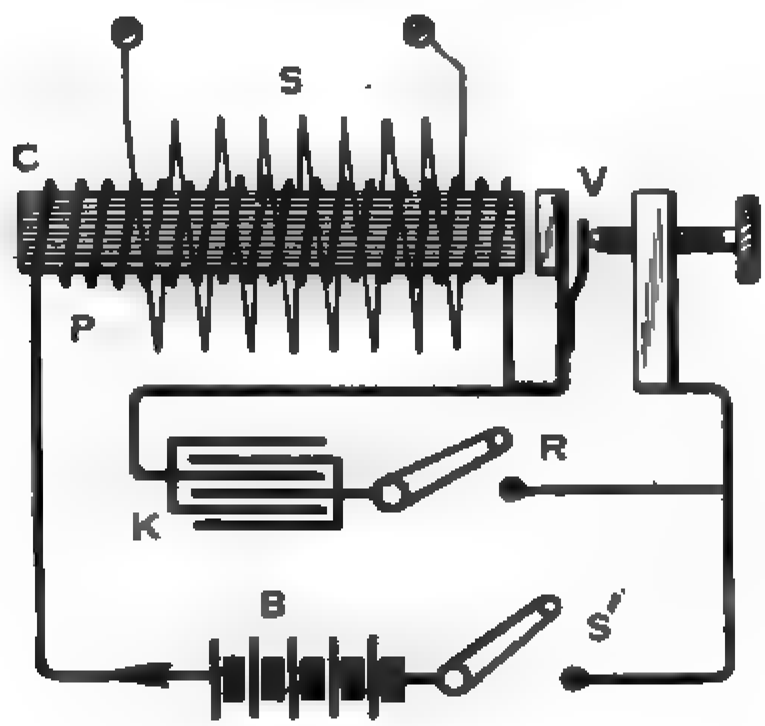


FIG. 675.—Circuits through induction coil.

varies with the magnitude of the secondary e.m.f. desired. It may be an ounce in a telephone coil or from 10 to 12 pounds in a 12-inch coil. No. 36 is employed because it is the smallest wire than can be handled without danger of breaking. Where the coil is machine wound, No. 40 enameled wire may be safely used. The interrupter may be similar to that employed in an electric bell, the armature being of soft iron attracted by the core when the circuit is closed. When it interrupts the circuit at the screw point in its forward travel, the core loses its magnetism as the current and flux collapse and a spring throws the armature back, closing the circuit again. The rate of interruption is very rapid. The induced e.m.f. depends upon the rate at which the

lines of force about the coil can be made to collapse. It is of the greatest importance that this rate of collapse shall be made the very maximum possible. Efficiency in an induction coil does not refer to the output compared with the input but to the ability to get a given length of spark with a minimum of material and current input.

When the circuit is first completed the primary current rises gradually from *A* to *B* as in Fig. 676. As the flux produced thereby cuts the secondary winding there is induced therein a wave of e.m.f. in the opposite direction, *A-F-C*. As the time, *A-C*, for the rise of current, *A-B*, is considerable, the magnitude of the induced e.m.f. *G-F* is small. When the current rising against the e.m.f. of self-induction reaches its maximum at *B* and is for a moment stationary, the induced e.m.f. falls from *F* to *C*. When the interrupter breaks the circuit, the current collapses from *B* to *E*, and with it the flux. If conditions are such as to insure a very short interval of time from *C* to *E*, during which the flux collapses, the magnitude of the induced e.m.f. in a positive direction will soar to a great height as from *C* to *P*, and when the current finally reaches zero at the point *E* the secondary e.m.f. collapses from *P* to *E* with it.

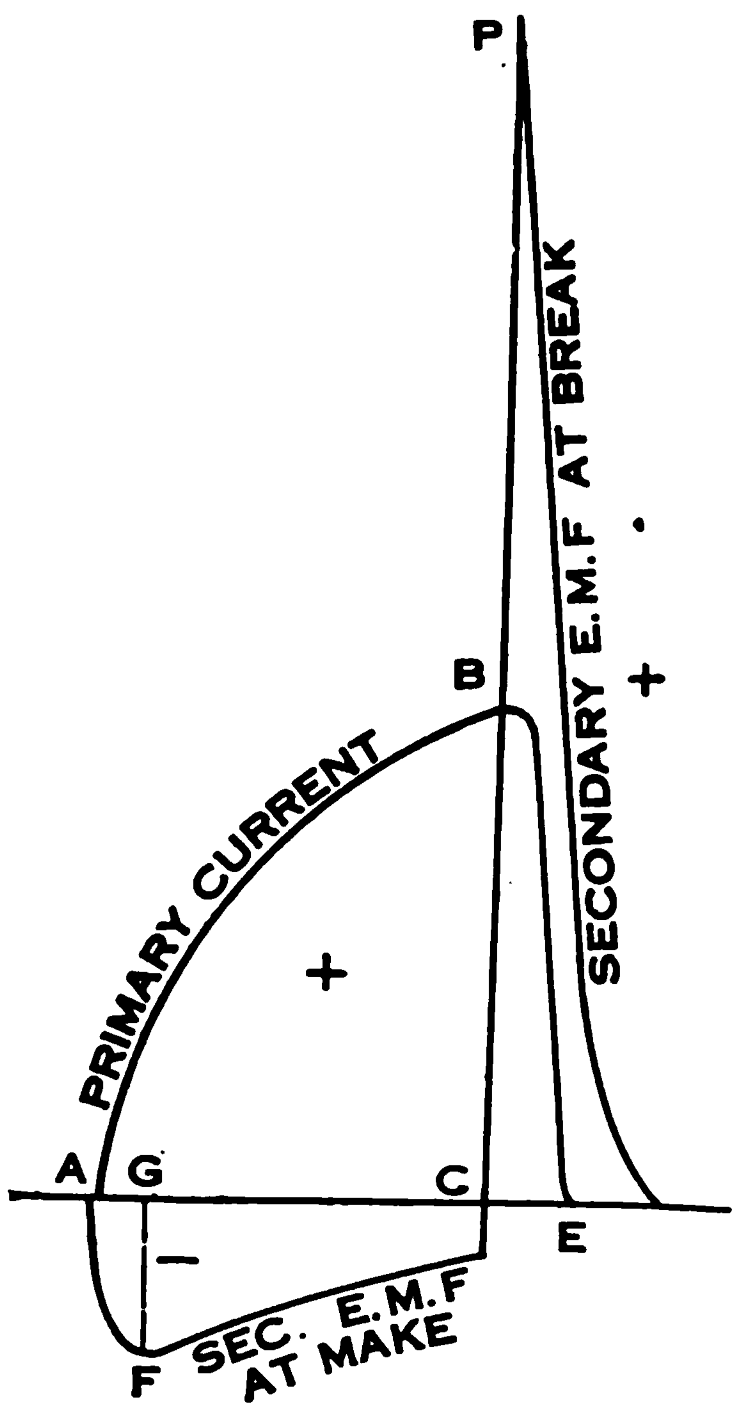


FIG. 676.—Relation between primary current and secondary e.m.fs.

It will be seen that while the current wave passes through a pulsation in one direction, as it is a unidirectional or undulating current, it brings about the induction of an alternating e.m f. Thus it is not necessary to supply an alternating current or alternating flux in order to generate an alternating e.m.f. A flux varying in magnitude from zero to a maximum of, say,

1,000,000 lines and back again to zero in a given time will induce just as much e.m.f. as will a flux of 500,000 lines rising to a maximum in one direction, falling to zero, rising to a maximum in the reverse direction and falling to zero again in the same time.

The negative wave of e.m.f., *A-F-C*, is so feeble as to be of little value in operations that require an induction coil. Hence it is neglected or suppressed entirely. Every effort is made to insure that the induced e.m.f. wave *C-P-E* shall be a maximum, for this is the wave that produces the spark for which the coil is designed.

The greatest attention should be paid to the insulation of the various portions of induction coils. Thus the core of iron should first be insulated with a tube, and over this the primary winding should be placed. Outside of the primary there should be a heavy tube of hard rubber or bakelite. Over this the secondary winding should be mounted. If the coil is to produce a spark several inches long, the secondary windings should be wound in sections as in Fig. 677. Each section should be from one-fourth to one-half inch in length, parallel to the core with layers of paper separating successive layers of wire. These sections should be subjected to heat and vacuum treatment to exclude every particle of moisture, after which they should be thoroughly impregnated with insulating compound. By having the successive sections wound in opposite directions it is possible to connect adjacent inside ends and outside ends together alternately throughout the series. This avoids the necessity of bringing the inside end of one section across the face between two coils to the outside end of the next section, which would involve a tendency to short-circuit between the inside and outside convolutions via this connection.

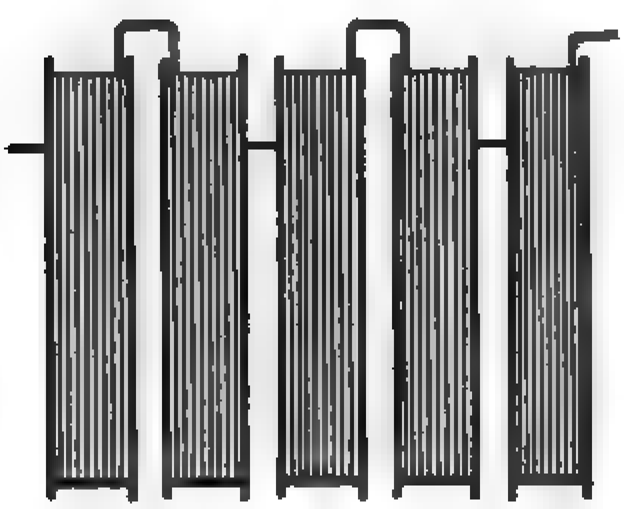


Fig. 677.—Arrangement of sections of secondary winding of induction coil.

The form of interrupter shown in Fig. 675 is not adapted for large coils because the rate of interruption would vary with the current employed. A preferable arrangement is the independent

form of interrupter shown in Fig. 678, which is connected in multiple with the coil. Here current is led through the terminal *B* and contact *C* via the wire *L* to the primary winding of the induction coil and thence out by the terminal *A*. The magnitude of this current can be adjusted at will by the screw *N*. In multiple therewith, the circuit for the interrupter leads through

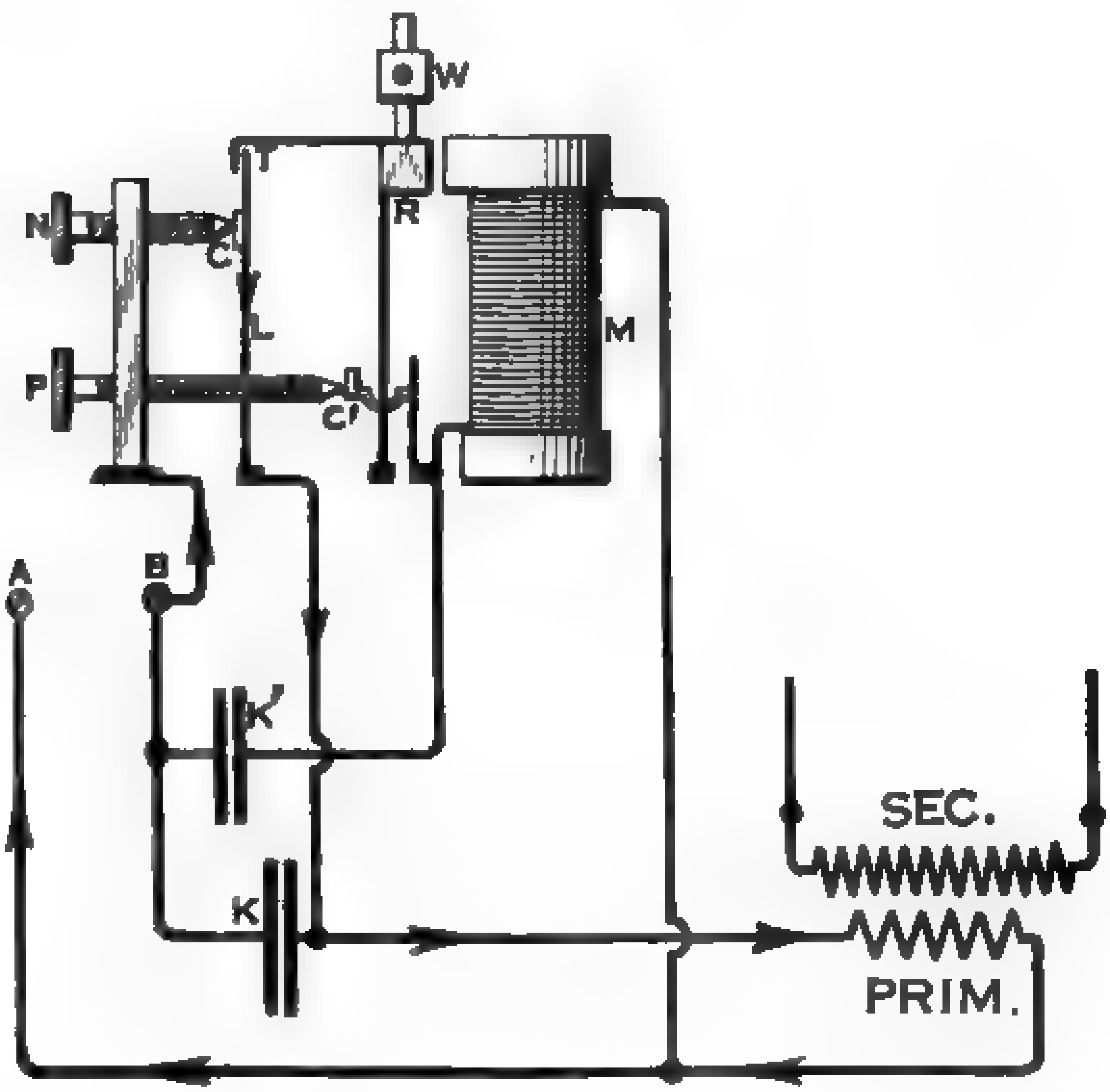


Fig. 678.—Diagram of circuits for induction coil employing Leed's multiple-independent vibrator.

the terminal *B* and contact *C'*, thence through the magnet *M* to the negative terminal *A*. The adjustments for this interrupter are made through the screw *P* which regulates the current therein, while the rate of interruption is adjusted by the counter-weight *W*, which may be raised or lowered. When the armature *R* is vibrating rapidly, it carries with it in its forward travel a hook which overhangs the point *T* After it has gained considerable velocity it strikes *T* in its forward travel and carries it forward,

sharply interrupting the circuit at the contact *C*. The rate of interruption and the magnitude of the primary current handled may be adjusted independently of each other.

An electrolytic interrupter devised by Dr. Wehnelt, possessing remarkable properties, is shown in Fig. 679. This takes the place of a mechanical interrupter and is connected in series between the source of supply and the primary of the coil. It consists of a jar containing a dilute sulphuric acid solution in which is an electrode consisting of a platinum point *P* not much larger than a pin head, which is sealed into the lower end of a glass tube through which an insulated wire leads to the external circuit. The positive side of the source connects to the terminal *A*. Another electrode *B*, which may consist simply of a lead plate, is placed in proximity to the platinum point and connects to the negative side of the circuit. When a current, either alternating or direct, is passed through the circuit in series with this device, an interruption of the circuit takes place with a rapidity of from 200 to 1,700 times per second. As the induced voltage in the coil depends upon the rate of interruption it is evident that this device will produce remarkably efficient results with any coil. The theory of operation is as follows:

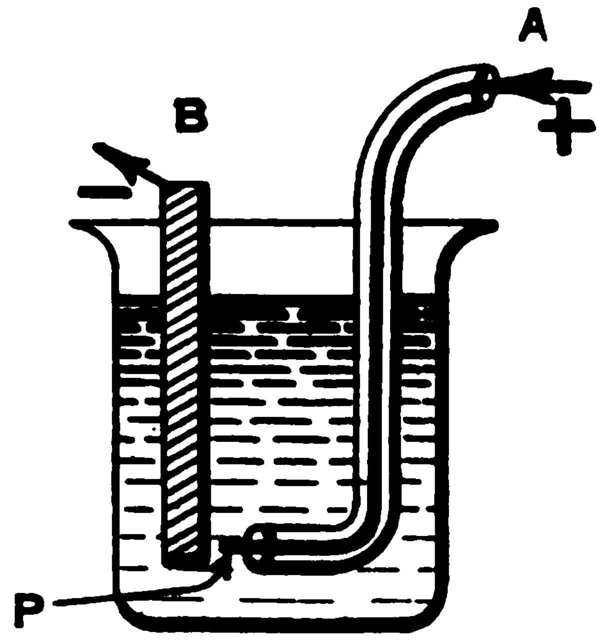


FIG. 679.—Wehnelt electrolytic interrupter.

When the current passes from the platinum point, the solution is decomposed and a gas bubble forms upon the exposed point, separating it from the solution and cutting off the current. The gas bubble is no sooner formed than it bursts. The solution surges in and the circuit is again completed. Decomposition immediately follows, and the cycle is rapidly repeated with the almost incredible rapidity above indicated.

A simple form of electrolytic interrupter is shown in Fig. 680 and can be constructed by drilling a hole in a glass tumbler with a No. 60 drill. This is placed in a larger glass jar, and both are filled with a dilute sulphuric acid solution. An electrode *A* is inserted in the inner tumbler and an electrode *B* in the outer tumbler. These electrodes may consist of lead or carbon. The

circuit is then completed from the source of the coil through the minute opening in the inner tumbler. The passing of the current causes the solution to be decomposed at the point of contact between the two solutions within the hole. This will for a short time satisfactorily handle 4 amperes on a 110-volt direct-current circuit. Due to molecular bombardment the hole gradually increases in size. When this happens the current increases in amount and the rate of interruption decreases. Thus the apparatus rapidly falls in efficiency. Furthermore, the solution becomes heated, which still further lowers the efficiency. Many forms of Wehnelt interrupter have been devised, some with very elaborate methods for cooling but none having proven very satisfactory in commercial use.

With a mechanical interrupter it is found that the secondary voltage is materially increased if the make-and-break is bridged with a condenser as at K, Fig. 675. The condenser is supposed to delay the rise of the current when the circuit is first closed, and thus suppresses the induced voltage at "make." Just how this is effected is not very clear. When the contact V is interrupted, however, the two coatings of the condenser offer considerable inducement for the charges which tend to pile up on these contacts, to flow into them where they will attract each other across the dielectric instead of building up and jumping across the contact points at V in the form of a spark. If allowed to jump the point of break, the spark would be drawn out and the interruption of the current would be gradual. When the condenser is used the charges surge into the condenser and effectually prevent a spark, and the break is made very sharp. This insures the induction of a maximum e.m.f. In Fig. 678 the condenser K is adjustable and is varied so as to reduce the spark at the contact C to a minimum. The condenser K' is small and cares only for the current in the interrupter magnet.

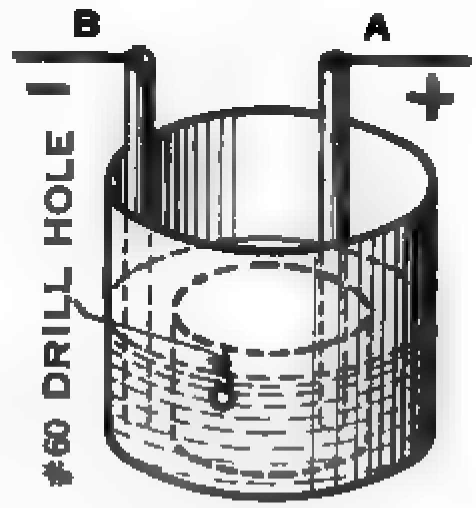


FIG 680.—Simple form of electrolytic interrupter.

It may be further stated that the advantage of the condenser lies in its ability to neutralize the self-induction of the primary

winding. It has already been noted in connection with the discussion of alternating currents that, in a circuit possessing inductance, the addition of capacity is desirable to neutralize the inductance. When so added in proper amount the circuit may be made to behave as though it possessed neither inductance nor capacity. As the self-induction of the primary of the induction coil is always present, the addition of a judicious amount of capacity is very effective in neutralizing it and thereby greatly enhancing the secondary spark.

SECTION XV CHAPTER I

TRANSFORMERS

INDUCTION COILS

1. Explain the principle of the induction coil. What is the name given to this form of induction? Give a diagrammatical sketch of an induction coil.

2. Show by curves the relation between the primary current and secondary voltage. Explain why these relations exist.

3. What is the object of using a condenser in connection with an induction coil? Explain its action. Give sketch showing condenser properly connected.

4. Explain the principle and operation of the "Leeds" multiple-inpendent vibrator. Sketch.

5. Explain the "Wehnelt" electroytic interrupter. Sketch.

6. Explain the construction of the Faradic medical induction coil. In what various ways may the secondary e.m.f. be altered?

7. What is the principle upon which the metallic sheath covering the core of an induction coil operates? Of what material is this sheath constructed? What is the effect upon the secondary e.m.f., if the sheath is removed from the core?

8. What various factors govern the induced e.m.f. in the secondary of an induction coil employing an ordinary make-and-break interrupter?

TRANSFORMERS

TRANSFORMERS-PRINCIPLES; TYPES

Following the classical experiments of Joseph Henry in 1832, the first transformers were devised. The first practical transformer was patented in England in 1882 by Gaulard and Gibbs. The American patent rights were purchased in 1886 by the Westinghouse Company. The first transformers in this country were built by William Stanley in 1885 while in the employ of the Westinghouse Company.

The transformer is a refinement of the induction coil. Like the induction coil, it has a primary and a secondary coil and an iron core. In the induction coil no attention was paid to efficiency as regards the output compared with the input. Length of spark produced by the secondary winding was the only thing that counted. In the transformer the greatest attention is given to efficiency. Transformers of large size have efficiencies in the vicinity of 99%—that is, they will deliver from one winding upwards of 99% of the power absorbed by the other winding. In the induction coil the magnetic circuit was only partly of iron and the rest was of air. In the transformer, the magnetic circuit of the whole core is of iron of large cross-section, while the copper coils are of low resistance. These things all contribute to high efficiency.

In the induction coil an interrupter was necessary to vary the flux in order to secure induction. As a transformer is designed to receive alternating current no interrupter is necessary. The transformer is employed simply to change alternating current of one voltage to alternating current of another voltage. It cannot possibly convert alternating current into direct current. In the induction coil the primary winding was always next to the core and the secondary winding around it. In the transformer these positions are often reversed because either winding may serve equally well as primary or secondary. The winding into which the original current is introduced is called the primary. The one in which current is induced is called the secondary. As these windings may be used inter-

changeably a further distinction is necessary. The low voltage winding is called the **low tension** (**L. T.**), while the high voltage winding is designated the **high tension** (**H. T.**). The relative number of convolutions in the two windings determines the **ratio of transformation.** Thus if one winding contained 100 turns and the other winding 200 turns, and 100 volts is impressed upon the first winding, 200 volts will be induced in the second winding. The ratio of transformation always refers to the voltage. The ratio of currents in the two windings is always the inverse of the ratio of the voltages.

While it is not practical to build alternators for more than 13,200 volts because of the expense of insulation, transformers may be built for very much higher voltages. The economy of high voltage in power transmission lines has already been pointed out. It is therefore desirable to raise the voltage as high as practical for long-distance transmission.

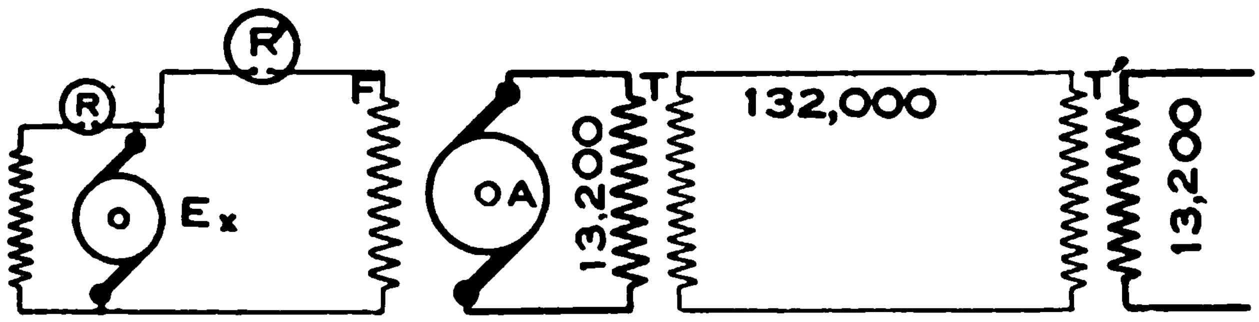


FIG. 681.—Alternator connected to raising and lowering transformers.

Assuming an alternator, *A*, in Fig. 681, to generate 13,200 volts, the current may be led into a raising transformer *T*, having a ratio of one to ten, thus stepping the voltage up to 132,000 for the line. At the distant point the current may be received on the high tension side of the reducing transformer *T'*, having a ratio of ten to one, which will lower the pressure again to 13,200. As the transmitting voltage is ten times the initial voltage, the copper required on the line will be only 1/100 as great as would be required had the voltage not been raised. It is evident that, if the transmission line is of any great length, he copper saved in the line will very soon more than offset ie cost of the raising and reducing transformers. As the ficiency of these transformers will be high, the power wasted transformation will also be very small compared with the would have been involved in the transmission line,

even though a greater percentage of copper loss had been allowed at the lower voltage.

The principle of the **static transformer,** so called because it has no moving parts, may be understood from a consideration of Fig. 682. Suppose an alternating e.m.f. of 100 volts is impressed upon a coil *A*, containing 300 turns. This will set up an alternating magnetic flux in the core *C*. This secondary flux, while occupying the cross-section of the path *C*, must not be considered as composed of magnetic lines having ends, which start out from the top of the coil and pass through its circumference, returning to the other end of the coil. They are magnetic rings or closed loops which originate around each convolution and expand like a stretched rubber band in widening circles until they not only cut all of the adjacent convolutions of *A* but extend across and cut all of the convolutions of the coil *B*, before they eventually occupy the cross-section of the core *C*. As these rings of force cut back and forth with the rise and fall of the current, they induce an electromotive-force in *A* and *B*. The induced e.m.f. in both of these windings is in the opposite direction to the e.m.f. impressed upon *A*. If the coil *B* is on open circuit, no effect is produced on the magnetic flux by the e.m.f. generated in *B*, but this generated e.m.f. in *A*, which is almost diametrically opposed to the impressed, backs out all the current save the minimum amount which is required to keep the flux oscillating. This is similar to the action of a shunt motor where the revolving armature generates an opposing e.m.f. almost equal to the impressed, the effective delivering just enough current to keep the armature going. In the case of a transformer, however, the conductors are stationary while the flux is kept oscillating.

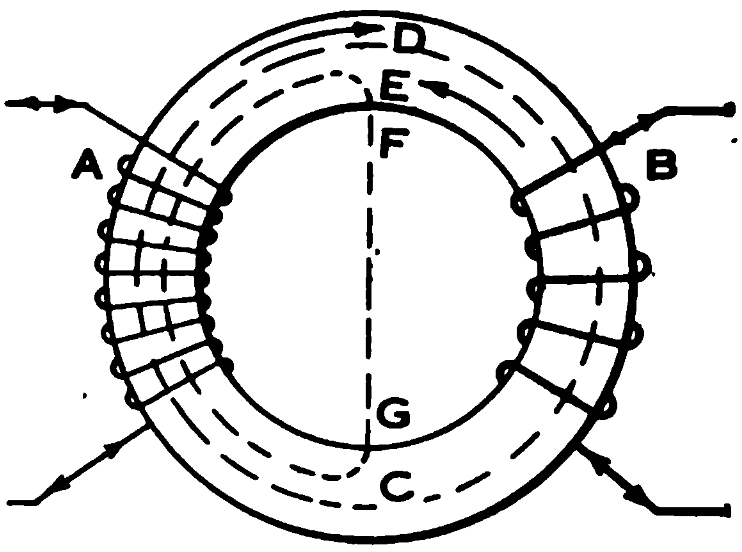


FIG. 682.—Principle of transformer.

The e.m.f. induced in the two windings is proportional to the number of turns. Thus if *A* possesses 300 turns and has impressed thereon 100 volts, and *B* possesses 150 turns, there will be 50 volts generated therein.

The actual voltage generated in a transformer winding is

proportional to the product of the total flux, the number of turns in the winding, the frequency of supply, and a constant.

Every convolution in each coil in a transformer is cut by the flux four times in each cycle: first, while the flux is rising in a given direction; second, while the flux is falling to zero; third, while the flux is rising in a reverse direction; and fourth, while the flux is falling to zero. Thus the **average voltage** which is generated in each winding with a flux having the **maximum value** of Φ will be:

$$E \text{ (avg.)} = \frac{4\,\Phi\,n\,T}{10^8}.$$

E = average e.m.f.
Φ = maximum magnetic flux.
n = frequency in cycles per second.
T = number of turns in coil.
4 = constant.
10^8 = constant to reduce absolute lines of force to practical volts.

If the wave of e.m.f. is a sine wave, the virtual voltage will be 1.11 times the average. This constant, 1.11, is called the **form factor** and varies with the shape of the alternator wave. The virtual voltage will therefore be four times 1.11, and this is the value which the voltmeter will register. As most alternators furnish a sufficiently close approximation to a sine wave, the constant 1.11 is sufficiently accurate for purposes of calculation.

The complete equation for the measured voltage generated in either winding of a transformer is therefore:

$$E = \frac{4.44\,\Phi\,T\,n}{10^8}$$

where E is the virtual e.m.f. and all the other letters have the same meaning as before.

If, now, a load such as an incandescent lamp is connected upon B, Fig. 682, a current will flow under the voltage induced. T is current will enable B to develop a magneto-motive-force which, according to Lenz's Law, is diametrically opposed to the magneto-motive-force of the current in A. Thus, if at a particular moment the current in A is endeavoring to send flux in the direction D, then at the same instant the magneto-motive-force of B will tend to send a flux in the direction E. Now as the

source of power is impressed upon A, B never succeeds in producing any flux. It simply produces a magneto-motive-force which opposes more or less the magneto-motive-force of A. Suppose at a given instant the tendency of A to produce a flux in the direction D is sufficient to develop 1,000,000 lines. If now, the current drawn from B develops a magneto-motive-force in the direction E, which would, if permitted, produce 100,000 lines, the net effect is to reduce the flux from 1,000,000 to 900,000 lines. If the counter e.m.f. in A induced by 1,000,000 lines admits just enough current to keep the flux moving, then when the reaction of B due to a current therein attempts to produce a flux in the reverse direction, the total flux circulating is reduced and with it the counter e.m.f. of A, which is dependent upon this flux. As the impressed e.m.f. remains the same, the actual current in the circuit A will increase because the effective e.m.f. has increased. This additional current increases the magneto-motive-force of A sufficiently to maintain the flux in the direction D and prevent the opposition in B from further reducing it. Thus the demand for current in B is promptly met by an automatic reduction of the counter e.m.f. of A, which takes in more current from the source of supply in direct proportion to the secondary load. If the load is disconnected from B, its opposing magneto-motive-force disappears. The large current in A now raises the flux, and thus a greater counter e.m.f. is generated in A. This backs out the superfluous current, reducing the net intake to the amount necessary to keep the flux oscillating. This small amount is called the **exciting current.**

It will thus be seen that a transformer will absorb current in its primary in direct proportion to the load on its secondary. In fact, A, B and C correspond quite closely to a direct-connected motor-generator set. A corresponds to a shunt motor, B to a shunt generator, and C to the coupling. The motor and generator are mechanically coupled. A and B are inductively coupled. If a load is placed upon the generator, the reaction of its armature will cause the speed of the motor to reduce, and with it the counter e.m.f. The motor will thus take more current to maintain the output of the generator and thereby prevent a further reduction in speed. In the case of the transformer a reduction of flux takes the place of a reduction in speed. As the shunt motor is practically constant in speed under variations in load,

so the flux in the core of a transformer is practically constant in value. The efficiency and regulation of a transformer, however, are much superior to that of a shunt motor-generator set. Hence the alteration in flux is a much smaller per cent than the corresponding variations in speed of a shunt motor.

As an illustration of the application of the fundamental formula for the e.m.f. of a transformer, consider a transformer having a capacity of 500 watts with a core of 3.125 square inches cross-section and a flux density of 41,290 lines of force per square inch. How many turns will be required on the low-tension winding for 110 volts with a frequency of 60 cycles? Transposing the original formula the number of turns required will be:

$$T = \frac{10^8 E}{4.44 B s n}.$$

T = number of turns in coil.
E = virtual e.m.f.
n = frequency in cycles per second.
B = flux density in magnetic lines per square inch.
s = cross-section of core in square inches.
4.44 = constant.
10^8 = constant to reduces absolute magnetic lines to practical volts.

To find the number of turns it is evident that the flux must be known or assumed. If a core of known cross-section is available, the flux density may be assumed and the product gives the total flux. Small transformers are frequently built to operate with the low flux density above mentioned. Others employ 80,000 to 90,000 lines. The lower densities, while reducing the loss per cubic inch of iron and thereby improving the operating efficiency, nevertheless involve a larger cost for iron in the first place.

Inserting the values above stated:

$$T = \frac{10^8 \times 110}{4.44 \times 41{,}290 \times 3.125 \times 60} = 320 \text{ turns}$$

for the 110-volt low-tension winding. If a higher density such as 80,000 lines be employed, the number of turns required would be reduced to approximately 165. The size of wire is ascertained by allowing a certain number of circular mils per ampere. If an

allowance of 1,000 circular mils per ampere be made and the transformer is designed for 5 amperes, then $5 \times 1{,}000 = 5{,}000$ c.m. which will correspond to No. 13 wire.

The high-tension winding for 1,100 volts will theoretically equal 320 times 10 or 3,200 turns, and for one-tenth the current this wire would have one-tenth the cross-section of the low tension, which would be No. 23. Practically, however, if the transformer is to be used for stepping down the voltage, the number of turns on the high-tension side must be reduced to allow for voltage losses in both high-tension and low-tension windings and for leakage flux between the two. Thus, instead of the 3,200 theoretical turns there might be 3,100 actual turns employed. A ten to one ratio would now give 3,100 to 310 turns the ratio necessary to reduce from 1,100 to 110 volts. But as the low tension has 320 turns the voltage induced in the extra 10 turns would compensate for the leakage flux and ohmic drop in the two windings at full load.

Therefore, if the design involved a reducing transformer for lowering the voltage, a certain number of turns must be **subtracted** from the high-tension or **added** to the low-tension winding to take care of the copper drop in both windings and the magnetic leakage.

If, on the other hand, the transformer is to be used for raising the voltage, the allowance must be made the other way, and a certain number of turns must be **added** to the high tension or **subtracted** from the low tension to give the proper voltage ratio.

Several points of similarity between the two windings of a transformer should be noted. If in Fig. 682 the winding *A* consists of 300 turns and a two to one ratio of voltages is desired, then *B* must consist of about 150 turns. The ratio of the currents will be the inverse of the ratio of the voltages. Thus, if the voltage ratio is two to one, the current ratio will be one to two. Hence, if *A* consists of No. 12 wire, then *B* must have twice the cross-section and consist of No. 9. If *A* has a total resistance of 0.5 ohm, then *B*, consisting of half as many turns of twice the cross-section, will possess one-fourth the resistance, or 0.125 ohm. This assumes the length of a turn to be the same in both windings.

As *B* contains one-half as many convolutions of a wire of twice the cross-section (neglecting extra insulation), it will occupy the same space on the core as *A*.

If A absorbs 10 amperes at 100 volts, its intake will be 1,000 watts. This will enable B to deliver 20 amperes at 50 volts, or 1,000 watts. Thus, neglecting the losses, the capacity of the two windings is the same.

Ten amperes circulating through 300 turns in A equals 3,000 ampere-turns; 20 amperes passing through 150 turns in B equals

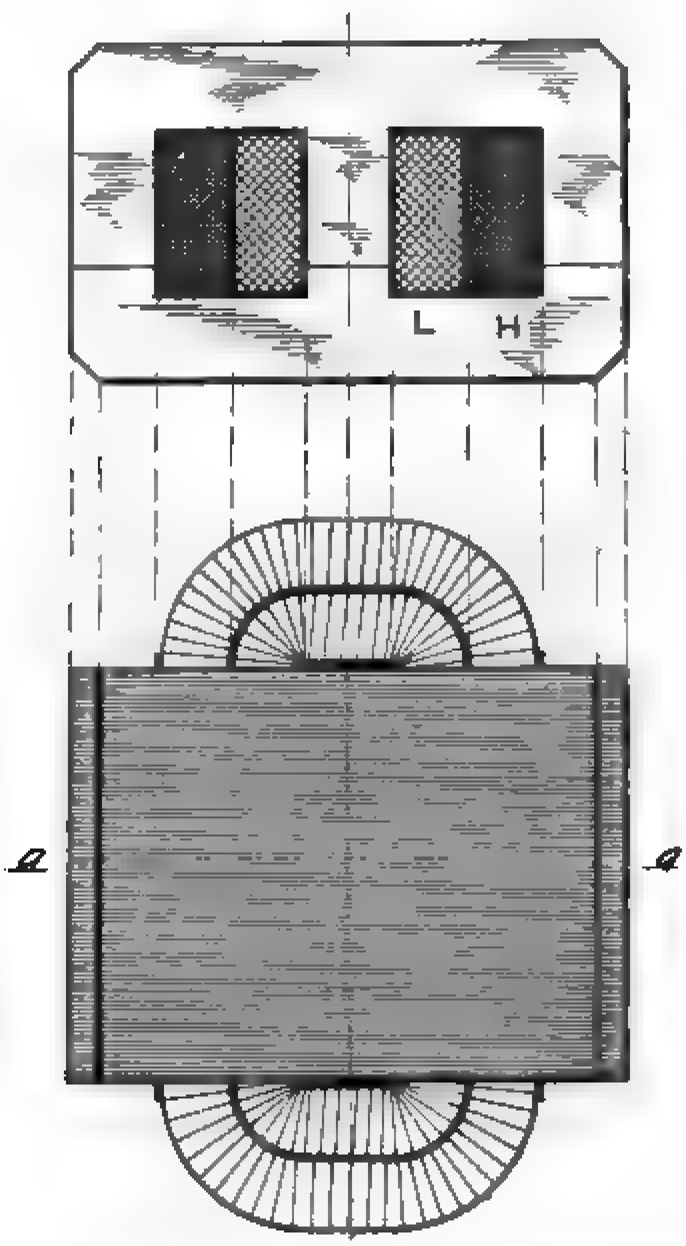


FIG. 683.—Plan and sectional view of shell-type transformer. Section shown is on line a-a.

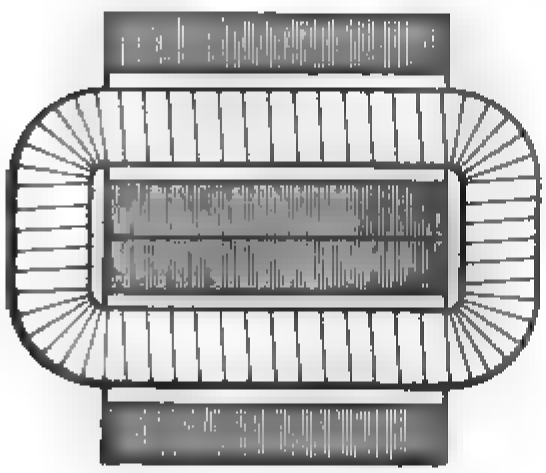
3,000 ampere-turns. Thus the ampere-turns of the two windings are the same.

As to the losses, $I^2R = P$ Thus $10^2 \times 0.5 = 50$ watts lost in A. $20^2 \times 0.125 = 50$ watts lost in B. Thus the power lost due to the resistance of the two windings is theoretically the same. Practically this is not usually true, as the length of

a mean turn is not the same in the primary and secondary windings.

Transformer Types

There are two general types of construction for transformers, the **shell type** and the **core type**. Fig. 683 represents the shell-type construction. Here the high-tension and low-tension windings *H* and *L* are wound on forms of circular or oval shape and the iron core built up of laminations interlaced through the center and around both sides of the coils providing a path for the flux. This is one of the earliest forms of commercial transformer, and some of the very largest and highest voltage types in use today follow the same general plan. In the larger sizes the iron core



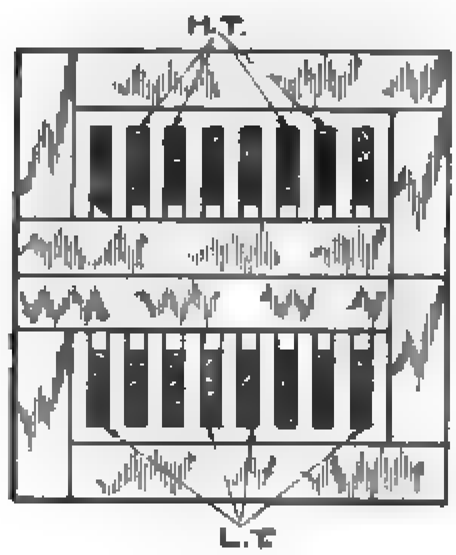


Fig. 684.—Improved form of shell-type transformer, showing provision for ventilation and interlacing of high-tension and low-tension windings.

is more extensive, often taking the form shown in Fig. 684. The advantage of this type is that a most excellent magnetic circuit is provided, but the copper, being largely surrounded by iron, must be thoroughly ventilated with ducts for the circulation of oil or air in order to radiate the heat.

The other form of construction is the core-type transformer illustrated in Fig. 685. Here a rectangular core is surrounded by coils, the laminations of the core being built up within the coils.

In all transformer cores the gaps due to the break in the magnetic circuit between the separate sections of the laminations are staggered in successive layers so as to reduce to a minimum the reluctance in the joint. In small sizes this type

of transformer core is made rectangular in cross-section, but in the larger sizes it is made in the form shown in Fig. 686. This provides ventilating ducts at *A* and *B* within the circular winding through which currents of air or oil may circulate so that heat may be radiated from within as well as from without the winding.

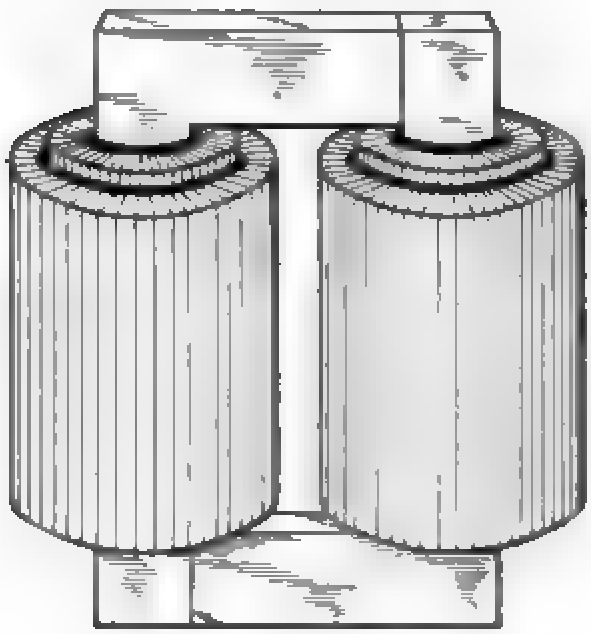


Fig. 685.—General plan of core-type transformer.

While in the shell type the copper was largely surrounded by iron, in the core type the iron is largely surrounded by copper. As the winding is thus exposed, the ventilation is superior in this core type to some shell types.

The high-tension and low-tension windings are not placed upon separate legs as shown in Fig. 682, but are equally distributed on both legs for the reason that, when currents are drawn from *B*, its magneto-motive-force reacts upon the magnetic flux tending to divert it in the direction of the dotted line *F-G*, which would constitute a path of leakage flux between the two windings. Now the voltage of *B* depends upon the flux which passes through it and, to whatever extent the flux of *A* is diverted from *B*, to that extent the voltage of *B* falls. From the standpoint of good regulation, therefore, it is highly important that all of the magnetic flux from *A* shall pass through *B*. By subdividing the high-tension and low-tension windings into two or more sections and placing half of each on each leg, whatever leakage flux takes place must pass between the inner

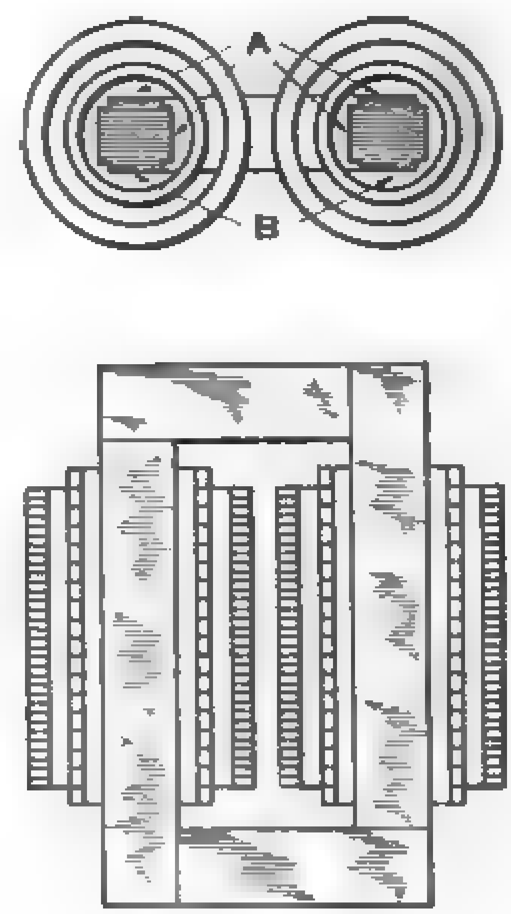


Fig. 686.—Plan and sectional views of core-type transformer

and outer sections of the windings on each leg. This insures that the leakage will be reduced to a minimum.

The arrangement is shown in Fig. 686. The low-tension winding is generally placed nearest to the core and the high-tension winding on the outside, the idea being to keep the high-

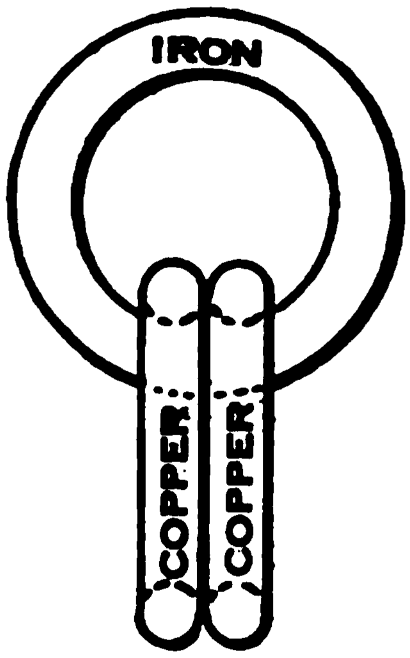


FIG. 687.

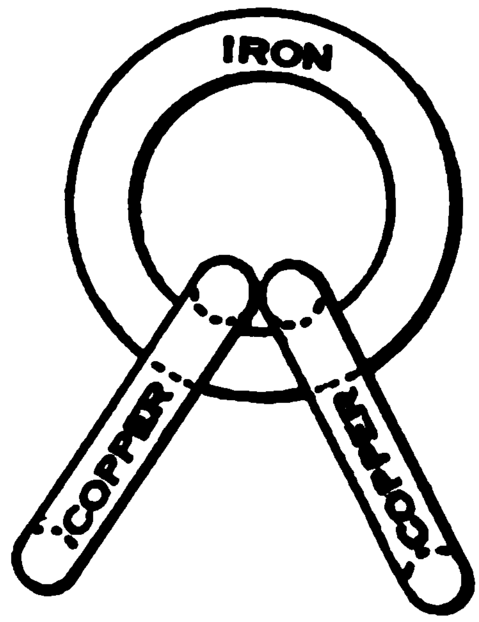


FIG. 688.

tension winding as far away as possible from the iron and thereby reduce the danger of grounding. Fig. 686 gives a good idea in plan and elevation of the core-type transformer.

Since the first few turns of the high-tension winding of a transformer are affected to a considerable extent by any high frequency line disturbances, it is the custom to increase the amount of insulation on the first few end turns or to insert a small reactance coil in series with each high voltage lead. These

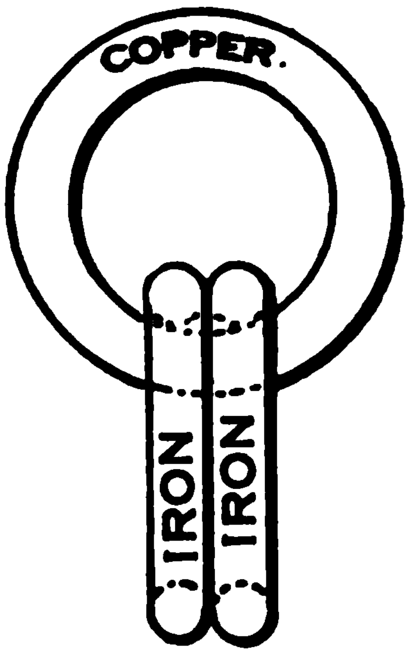


FIG. 689.

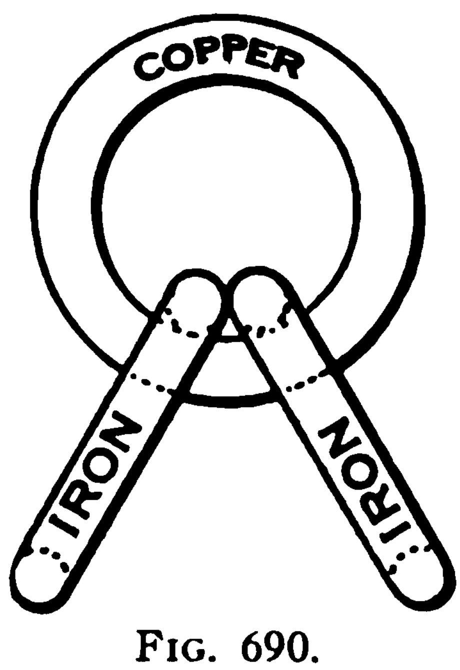


FIG. 690.

reactance coils are external to the main structure of the transformer but mounted inside of the case.

The difference between these two types may be seen by considering Figs 687 to 690. Consider a ring of iron in Fig 687 with two copper rings, one representing the primary and the other the secondary, linked therein If these two coils are swung apart on the iron core, the result will be a core-type transformer as shown in Fig. 688, if, on the other hand, the iron ring of 687 is replaced by a copper ring, 689, and the two copper rings of 687 are replaced by two rings of iron, 689, then if these iron loops are swung apart the result will be as shown in Fig. 690, and the copper winding is largely surrounded by iron, whereas the iron link in Fig 688 was largely surrounded by copper

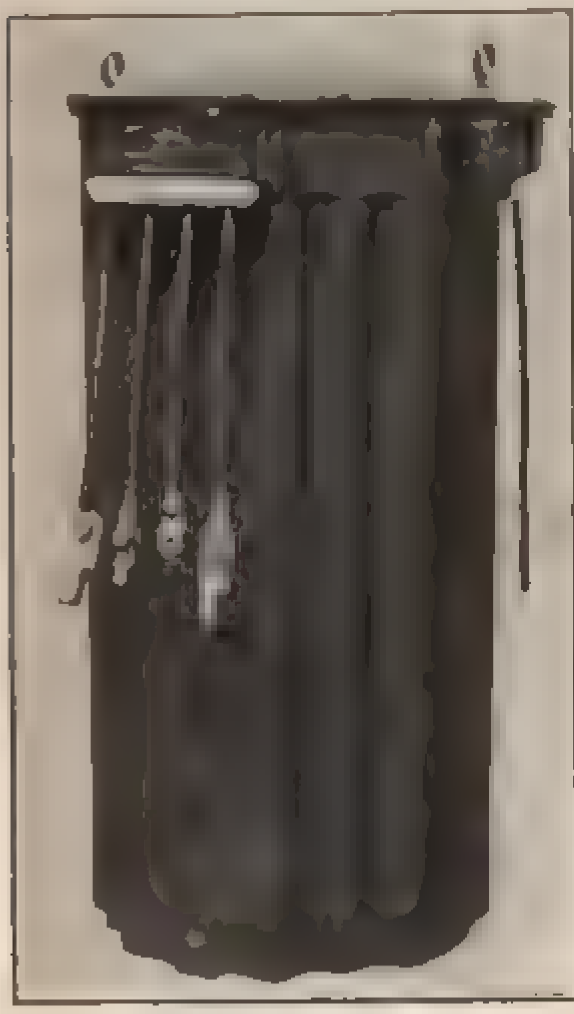


Fig 691 — General appearance of standard pole type, single-phase transformer, manufactured by The General Electric Company

Fig 688 is the plan of a core type of transformer, while Fig 690 represents the shell type. Each has certain advantages and also certain defects. A very satisfactory compromise between the two has been widely adopted for transformers of moderate size. This is known as the cruciform core type and is pictured in Fig. 692. Here the winding is concentrated upon a central limb, and the magnetic circuit divides through four paths in multiple There is rather more iron than in the core type, while somewhat less than in the shell type The ventilation is not quite so good as in the core type but better than in the shell type The interlocking of the laminations on the top and bottom of the core is shown in the top view of this type, Fig. 693.

Small bell-ringing transformers taking current from house-lighting circuits at 110 volts and transforming to 6 volts for operation of door bells are generally constructed of the shell type after the plan shown in Fig 683 For operating small elec-

tric toys these transformers are often provided with taps from the secondary winding so that 6, 12 or 18 volts may be obtained.

The very largest transformers are often built of the shell type with ample provision for ventilating ducts both through the laminations and between sections of the windings as shown in Fig. 694. Only thus can the large amount of heat generated therein be successfully radiated.

FIG. 691 represents the outside appearance of a core-type single-phase transformer designed for mounting on poles, and manufactured in sizes from 25 to 50 k.v.a. capacity by the General Electric Co.

Transformers are usually mounted in cast or sheet iron cases. These cases may or may not be filled with oil. Most transformers have their cases filled with a high grade of mineral oil. Its advantages are as follows.

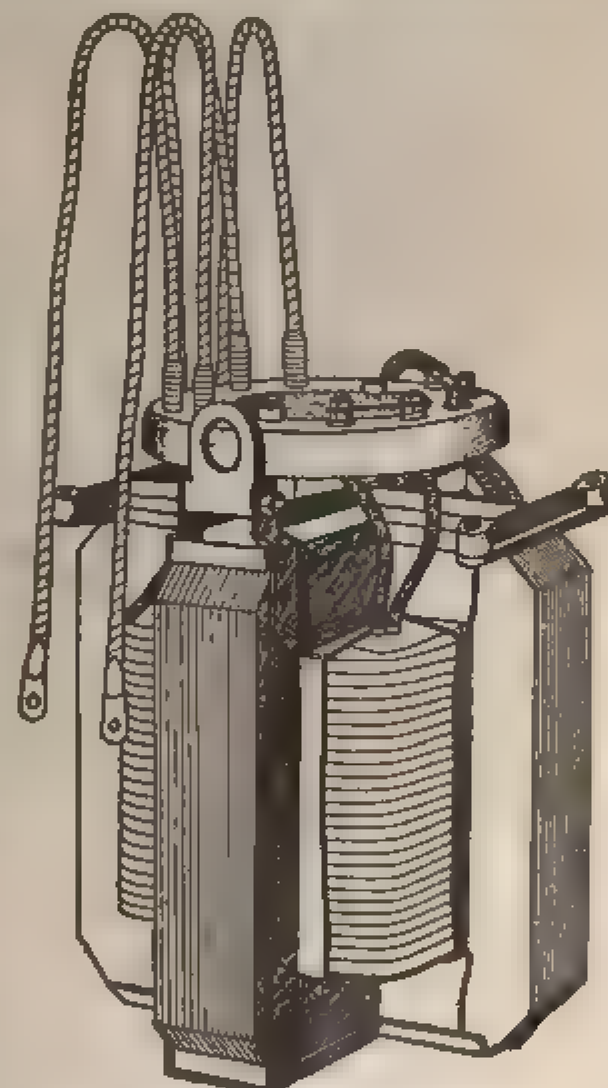


FIG. 692. General appearance of modified core-type transformer, using the "cruciform" core.

First, it reduces the temperature. The oil next to the windings is heated and rises to the top of the transformer, where it is replaced by the cooler oil from against the outer case which descends to the bottom and replaces the heated oil around the windings. A natural thermo-circulation is thus set up which rapidly carries off the heat generated and distributes it over the surface of the case from which it is radiated.

Second, oil preserves the insulation against oxidation. At high temperatures the cotton insulation of the wire tends to carbonize. The presence of oil and the lowered temperature which it brings about lessen this tendency. **Third,** it increases the insulation resistance. The dielectric strength of oil is several times that of cotton. There is less tendency for insulation to break down when it is thoroughly saturated with a good oil.

Fourth, it reinsulates punctures. If a discharge takes place between convolutions of separate sections due to a high voltage surge, a charred path may be left through a solid insulation over which another discharge may readily follow. Where oil is present it immediately flows in and reinsulates the puncture, after which its resistance to breakdown is practically as good as at first.

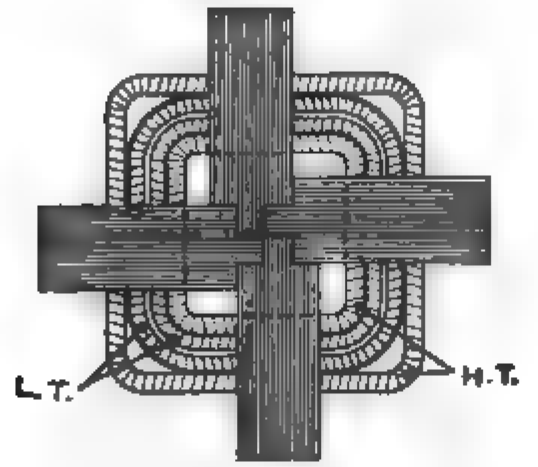


FIG. 693.—Sectional view of "cruciform" core-type transformer, showing method of uniting the magnetic circuits and relative positions of high-tension and low-tension windings.

Too much attention cannot be paid to the selection and care of the oil employed in transformers. Mineral oil has generally been found satisfactory. It has been almost universally adopted as the proper oil for transformers. In the selection of the grade to be used, the main points to be considered are dielectric strength, flashing point, viscosity and sludging. Of these the dielectric strength pertains to the insulating properties, the flashing point to the safety in operating from the standpoint of fire, viscosity and sludging to the fluidity which will influence it as a circulating and cooling medium and the residue which may accumulate due to carbonizing.

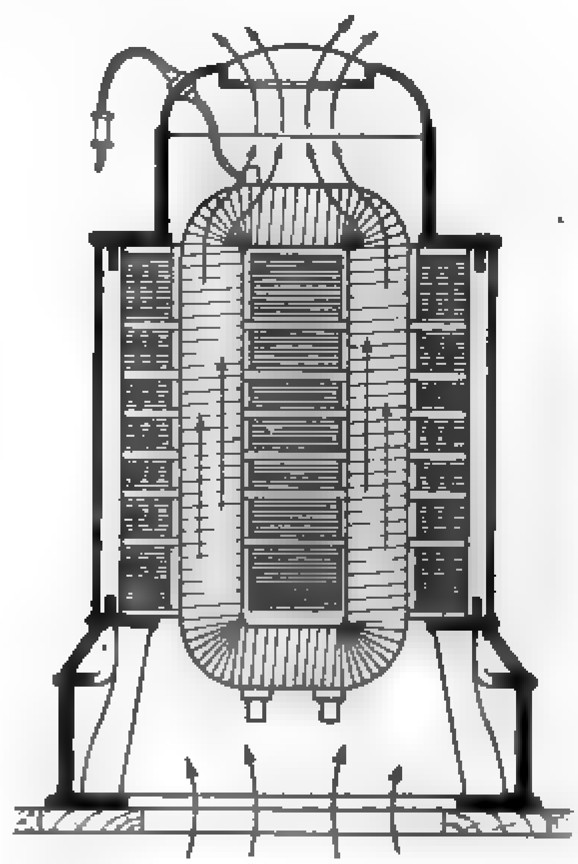


FIG. 694.—Air blast type of transformer, showing ventilating ducts for circulation of air.

In order to have a high dielectric strength oil must be free from water, sediment, sulphur, acids and other impurities. As rubber contains sulphur for its vulcanization, it should never be used for insulating any part of a transformer where it comes in contact with oil. The principal impurity found in transformer

oil is water. The old adage that "oil and water will not mix" does not seem to apply in the case of transformer oil, for the presence of 1 part of water in 2,500 parts of oil will result in a reduction of the dielectric strength of the oil to about one-half that of its pure state. Notwithstanding the greatest precautions, more or less moisture gets into transformer oil, and elaborate methods are used to eliminate it and thus prevent the breaking down of the insulation of the windings.

In 1920 transformers had been successfully designed and constructed for a maximum potential of 220,000 volts with oil insulation. As to size, the largest transformers in service (1921) are

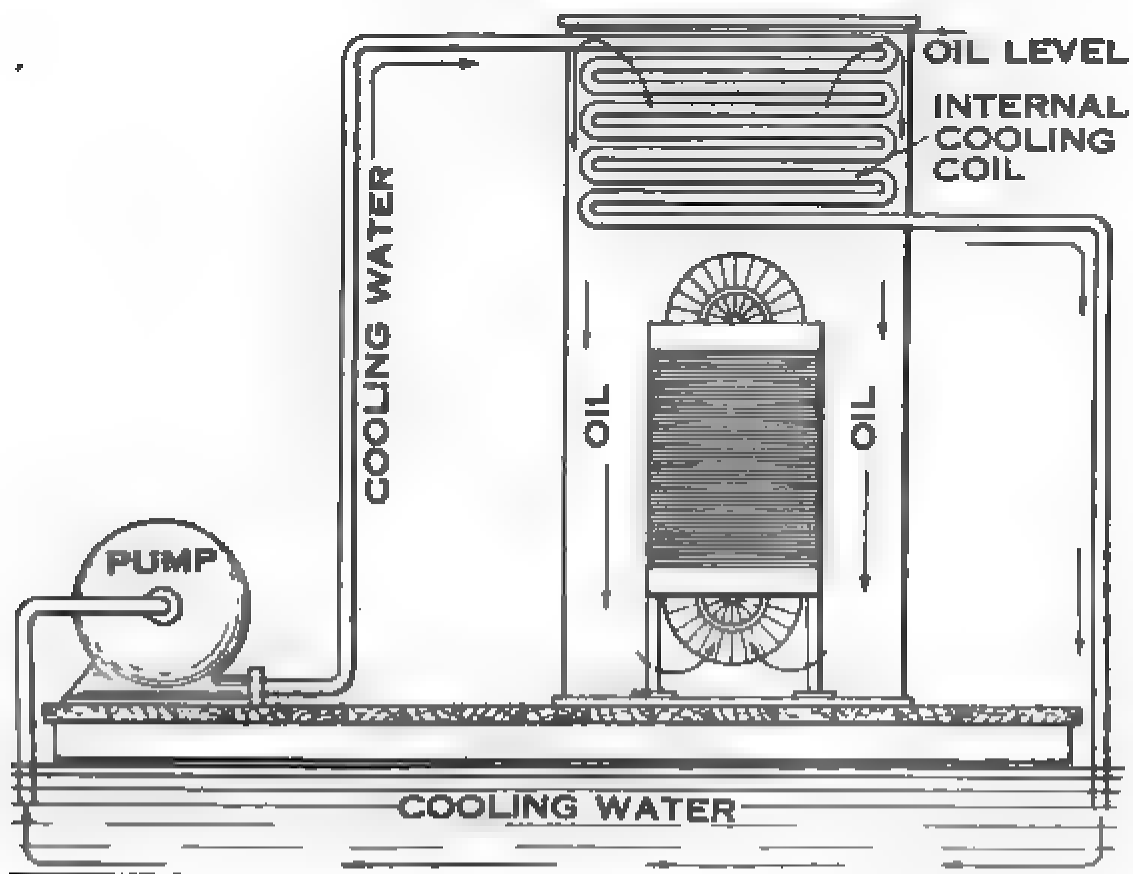


FIG. 695.—Oil-insulated, water-cooled transformer, showing system for circulation of cooling water.

those of 25,000 K.V.A. rated capacity in the plant of the Detroit Edison Company, which, while designed for this rated capacity, have an effective output of 50,000 K.V.A They have a voltage ratio of 24,000 to 1,200.

The problem of radiating the heat generated in the windings of a transformer is serious. Notwithstanding the high efficiency there is considerable energy transformed into heat which must be radiated to prevent an injurious rise in temperature.

Cooling of Transformers

Transformers may be cooled in several ways:

First: By natural radiation of the heat from the coils through the air in the transformer case without oil. Many of the early transformers were so constructed, especially in small sizes. They were kept tightly closed so as to exclude moisture, and when the energy to be radiated was small they gave fair satisfaction.

Second: Transformers may be cooled by natural circulation of the oil with which the case is filled, as previously outlined.

Third: Transformers may be cooled by means of an air blast through the case which contains no oil. This construction is illustrated in Fig. 691, where air is forced under pressure through an opening in the floor up through the transformer and out at a vent in the top. Where this forced draft is employed a much greater output for a given amount of iron and copper is possible than where oil is employed. The transformer, however, is somewhat more bulky for its output, and the system is not entirely satisfactory. The first Niagara Station, the Detroit Edison Station, and many others used transformers of this type some years ago. But several disadvantages were encountered. Although the air was cleaned before its introduction into the transformer, a certain amount of dirt inevitably adhered to the walls of the air ducts. This facilitated break-down and tended to sustain a flame should a short circuit occur. Moreover, if an arc started, the air draft fanned it and increased the tendency to destroy the insulation. If the blowers stopped, the temperature of the winding rose rapidly. Air-blast transformers have not generally proven satisfactory at potentials above 35,000 volts.

Fourth: Transformers may be cooled by circulating water through a system of pipe coils placed in the top of the transformer case, the case itself being filled with oil, Fig. 695. The water, after absorbing the heat from the oil, is forced by a centrifugal pump to a cooling tank where it dissipates the heat, after which it is again pumped through the pipe system.

Fifth: Occasionally the oil is pumped off from the top of the tank, circulated through a system of radiators to cool, and returned to the bottom of the case. The disadvantage of this method is the danger of a break in the system causing the loss of oil and the admission of moisture, which would endanger the operation of the transformer.

Sixth: In a number of instances an automatic circulation of the oil externally has been satisfactorily obtained by connecting to the case a series of pipes extending vertically from the top

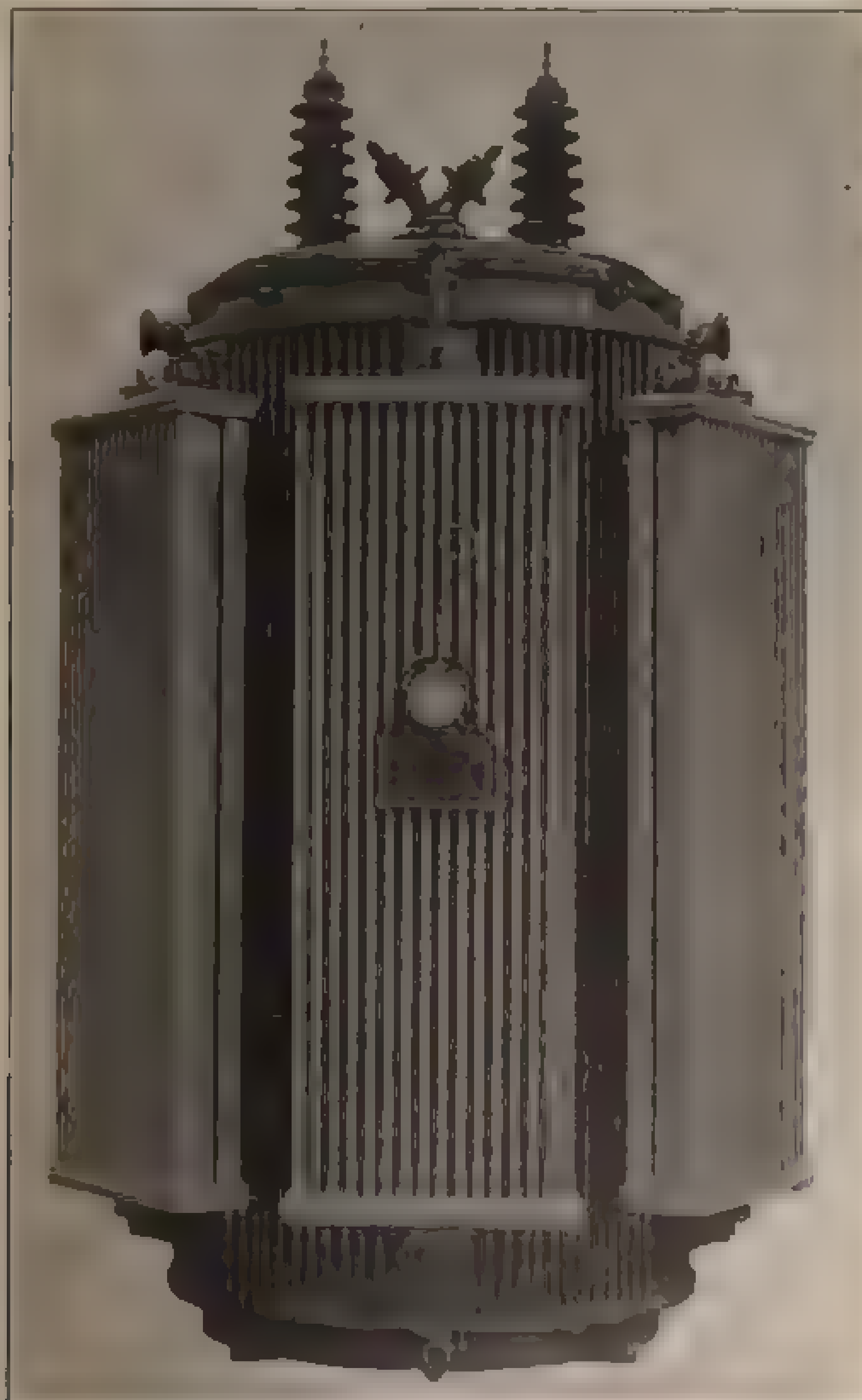


FIG. 696 General Electric radiator type of transformer, showing provision for thermo circulation of oil through radiators attached directly to transformer

to the bottom of the transformers. The heated oil passes out at the top, down through the pipes, losing its heat en route and returning to the case at the bottom. Fig. 696 shows a large General Electric transformer of this kind. This is the so-called "radiator" type.

A phenomenon known as **"ageing"** or **"metallic fatigue"** of iron and steel has given a great deal of trouble in connection with the operation of transformers. It had been observed that the core losses in a new transformer, while quite small to begin with, would steadily increase for the first ninety days of its use, during which time the losses might rise to double the original value. Investigation of the subject brought out the following facts: (1) There is unquestionably an increase in loss notwithstanding every precaution in design. (2) A great difference exists in the amount of ageing taking place in different qualities of iron and steel when maintained at the same temperature. (3) This increase in the loss in a given body of iron is dependent upon the

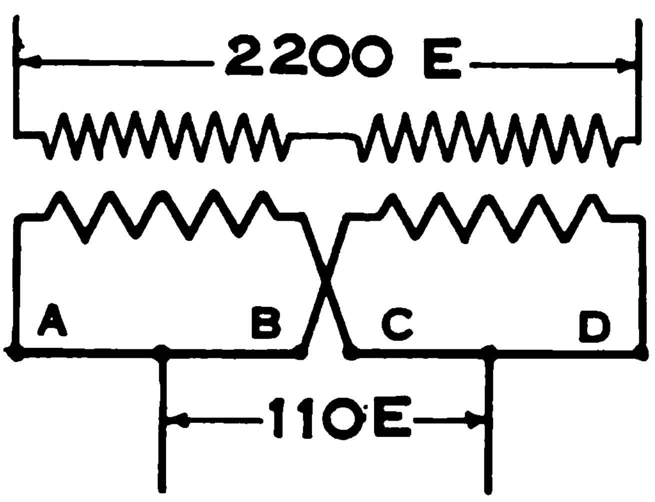


FIG. 697.—High-tension windings in series, low-tension windings in parallel.

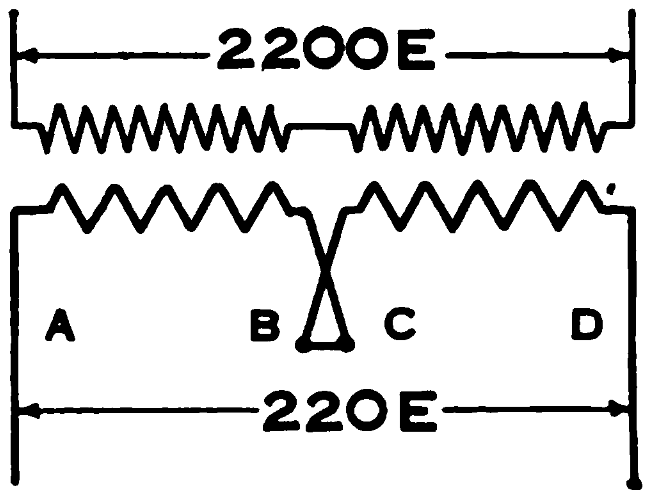


FIG. 698.—High-tension windings in series, low-tension windings in series.

temperature at which it is maintained. (4) Within ordinary limits of temperature, the tendency to ageing increases with the temperature. (5) Soft sheet steel is much less subject to ageing than soft sheet iron. (6) Sheet steel does not age materially at temperatures under 75° C., but almost any iron or steel will age more or less at higher temperatures. While many of the laws governing ageing have been determined, the real cause has not been discovered.

Arrangement of Coils

The high-tension and low-tension windings of transformers are generally divided into at least two sections. The separate sections of either winding may be connected in series or in par-

allel. This gives at least two fundamental voltage adaptations on either side of the transformer. In Fig. 697 the two high-tension sections are shown connected in series and adapted for, say, 2,200 volts. The two low-tension windings are designed for 110 volts each and are connected in parallel. The leads from the high-tension windings terminate upon a connection board of porcelain in the top of the transformer inside the case and generally come out at the back of the transformer case. The cover must be removed to change the high-tension connections. The terminals of the low-tension windings generally protrude through the front of the case and are arranged so that they may easily be connected in series or in parallel. If, instead of connecting *A* and *B* together, which are corresponding ends of the two low-tension sections, and *C* and *D* together, which are the other corresponding ends, so that the sections are in parallel, *B* and *C* are connected together as in Fig. 698, and *A* and *D* lead direct to line, then the two low-tension sections are thrown in series and will deliver 220 volts. The separate sections of the high-tension winding or the low-tension winding may be connected either in series or in parallel without respect to the way in which the other winding is connected.

Early central stations employed a large number of small transformers, each of small capacity supplying an individual

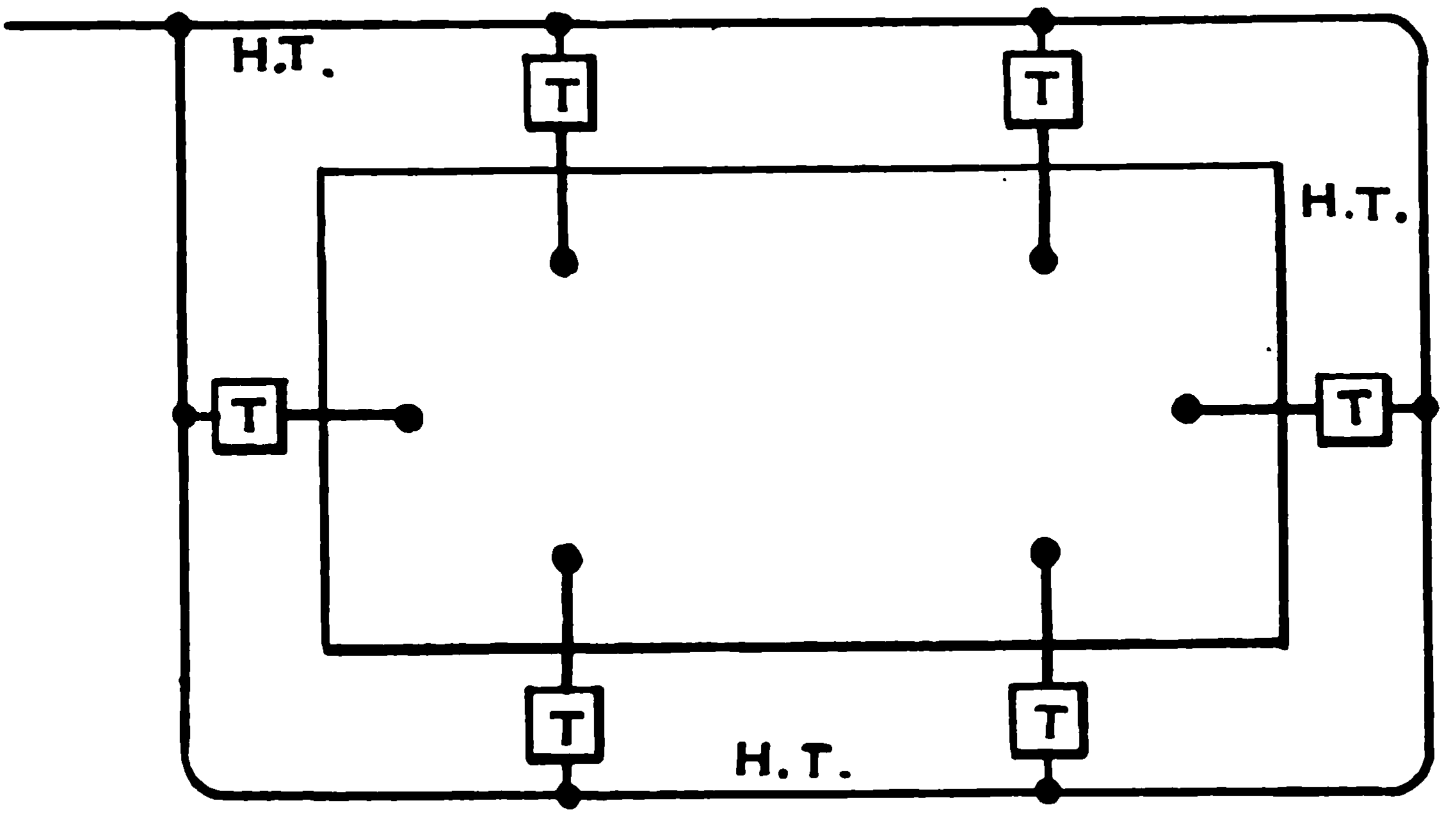


FIG. 699.—High-tension network with small-size individual transformer for each customer.

house or store. As a transformer of 500 watts may have a full load efficiency of not over 90%, and as many houses do not use

current during the day, the early stations were heavily loaded due to the core losses of a large number of very inefficient small transformers. This arrangement is shown in Fig. 699, where a high-tension distributing network, represented by a single wire

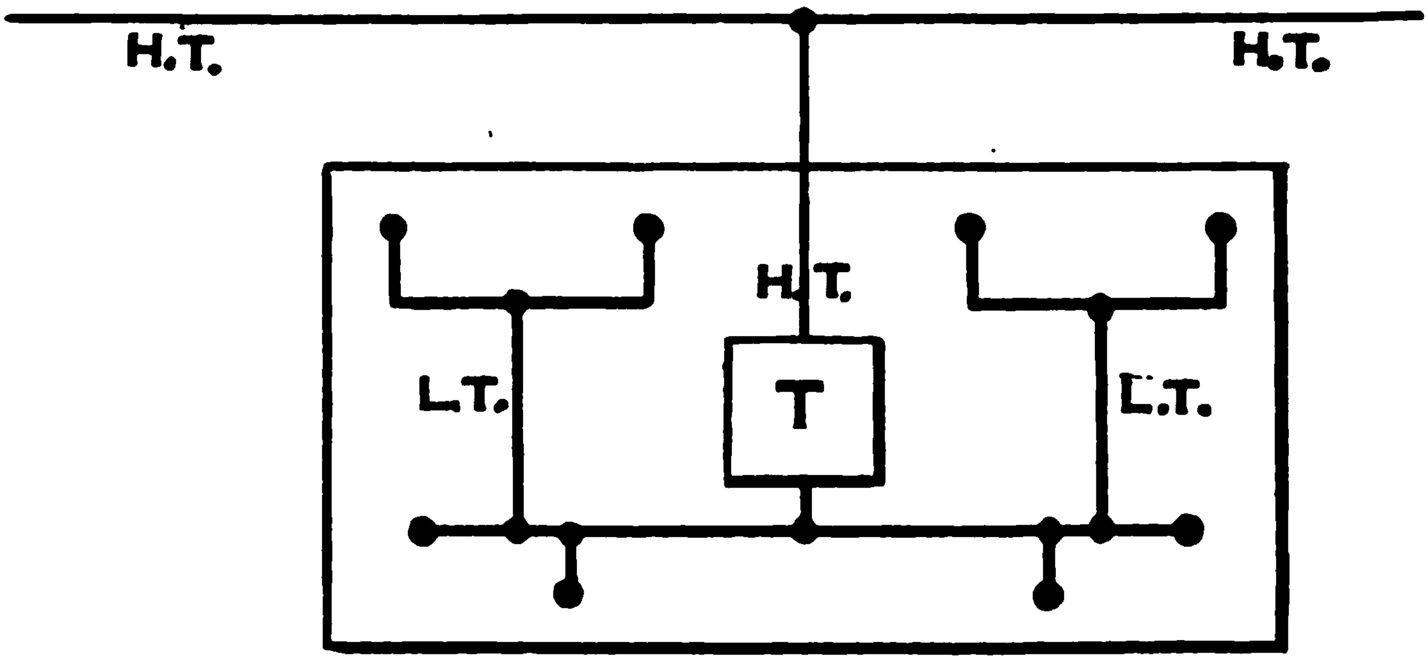


FIG. 700.—One large transformer and low-tension network supplies all customers in block.

marked *H-T*, extends around all sides of a city block and from which taps are taken to small transformers at each house, the voltage being stepped down before entering the house. Of course

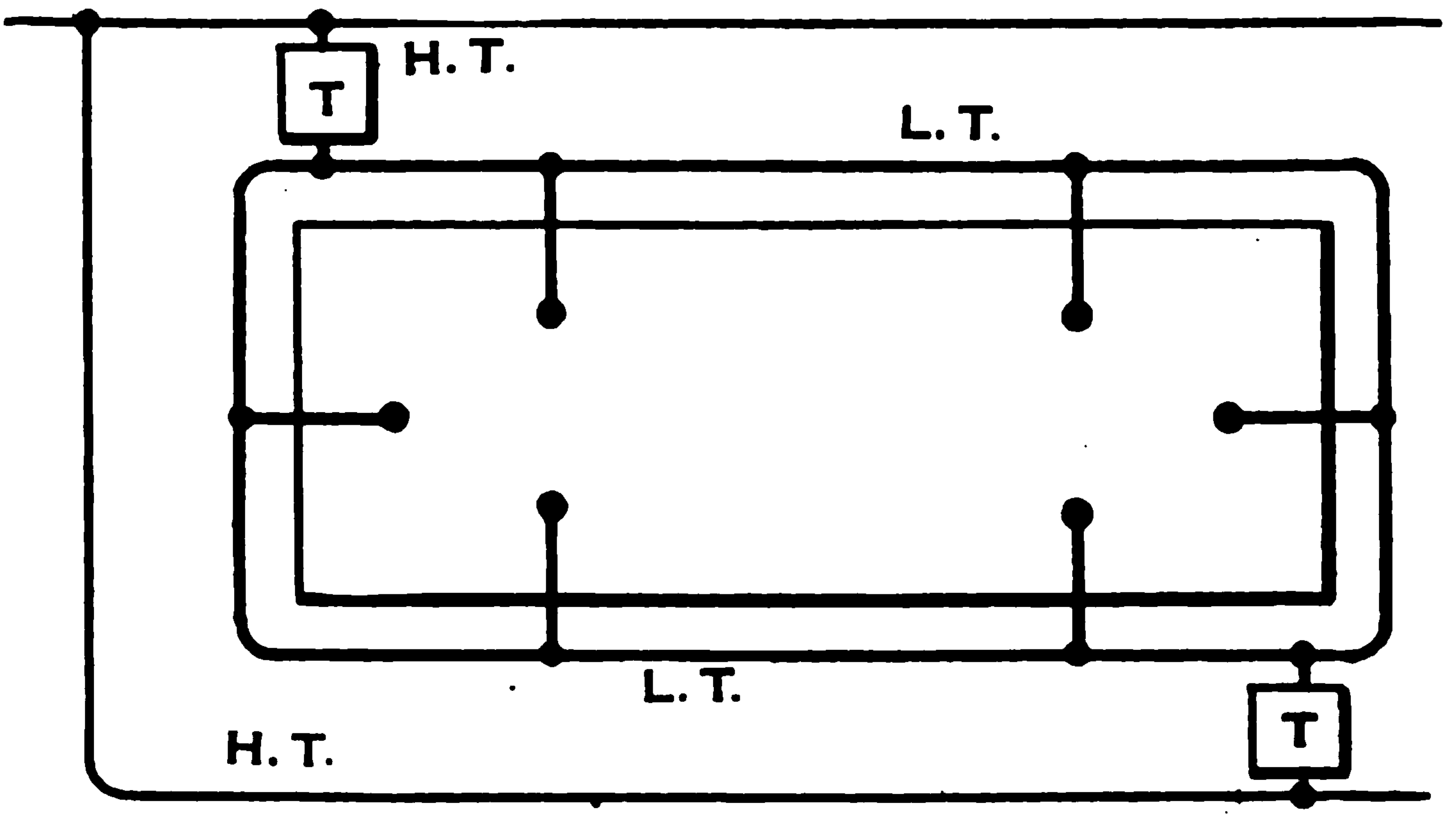


FIG. 701.—High-tension network and low-tension network interconnected through a few large-size transformers.

the circuits are all two-wire circuits, the single-wire diagram being used for simplicity. It was soon discovered that one large transformer could be located in the center of a block, as shown in Fig. 700, with a high-tension supply, and from the transformer a

low-tension network could be taken which would supply all of the houses in that vicinity. If this transformer has a capacity of 20,000 watts, its half-load efficiency could readily be 97%. The larger transformers proved such an economy that the small transformers were soon abandoned, and the saving effected in a comparatively short time defrayed the expense of the new trans-

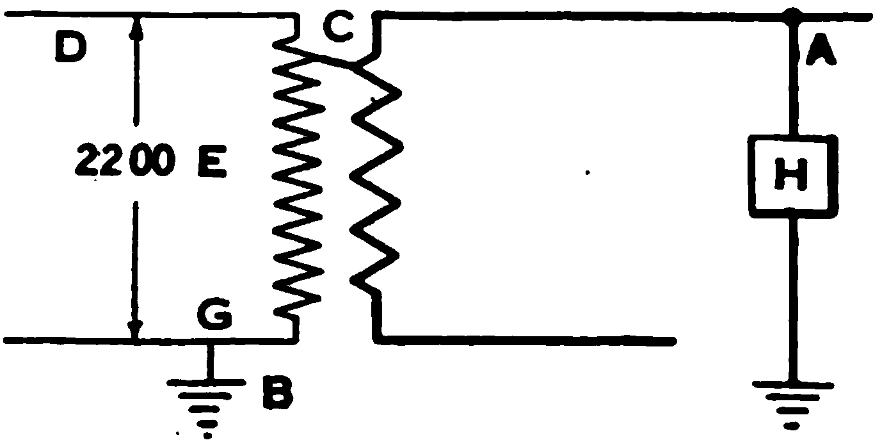


FIG. 702.—Illustrating how a ground between high-tension and low-tension windings of transformers may admit high voltage to low voltage circuit.

formers. The custom at present is to have the area to be supplied covered with a high-tension alternating-current network, stepped down through a few lowering transformers to the working potential of 220 volts. The low-tension network covers the same area as before and is fed from the transformers connected

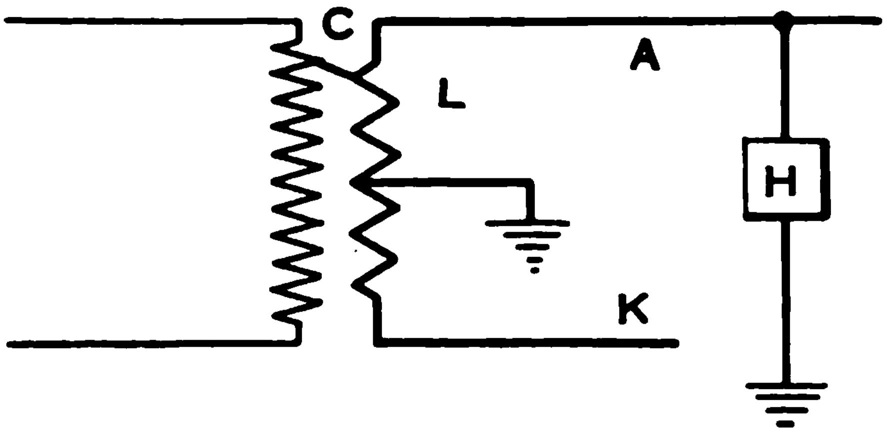


FIG. 703.—Showing how grounding of low-tension winding effectually protects low-tension system from high voltage.

in parallel both on the high-tension and low-tension sides, as shown in Fig. 701.

Should the insulation between the two windings of a transformer break down as at *C*, Fig. 702, and a person touch one wire of a low-tension system as at *A*, while standing on the ground, and the high-tension side of the transformer supplying this circuit be grounded as at *B*, then the entire potential difference

of 2,200 volts between the wire *D* and the ground point *G* would be impressed upon the person at *H*, in contact with the point *A*. Many persons were accidentally killed in this way with high-tension currents before proper precautions were taken, although the person came in contact with the low-tension side only. To guard against this contingency, the middle point of the low-tension winding is grounded as in Fig. 703. This insures that the maximum potential between a person who is connected to the ground and either one of the wires *A* or *K* will never be greater than one-half of the low-tension voltage. Now, even though the two windings be connected together at the point *C* by lighting discharge or otherwise, the fall in potential through the section of the winding *L* from the high-tension side will never be greater than the inductive drop therein, so that a person touching the wire *A* and connected to the ground will always be protected by this by-path or inductive shunt through *L*.

SECTION XV CHAPTER II

TRANSFORMERS

PRINCIPLES. TYPES

1. Explain the construction and principle of operation involved in a static transformer. Sketch.
2. What is the "ratio of transformation" in a static transformer? What governs this ratio? What are the relative sizes of wire on primary and secondary? What are the relative number of convulation of wire on primary and secondary?
3. Explain why the current taken by the primary of a transformer is proportional to the current furnished by the secondary.
4. A transformer has 2,000 turns in its high tension winding and is connected to a 2,200 volt, 60 cycle, A. C. line. How many turns must the low tension have to deliver 220 volts and what will be the frequency of the secondary current, neglecting losses?
5. A transformer has 6,480 turns in its high tension and 108 turns in its low tension winding. It is connected on the high tension side to a 6,600 volt line and absorbs 20 amperes. What will be the voltage and current delivered by the low tension, neglecting losses?
6. A transformer has 3,240 turns in its high tension and 216 turns in its low tension winding. It is connected on the low tension side to a 110-volt line and absorbs 106 amperes. What will be the voltage, current,

and power delivered by high tension, and power absorbed on the low tension side, neglecting losses? Power factor unity.

7. Give the fundamental transformer formula for the virtual voltage generated in a coil when a flux varies through it. Tabulate the meaning of each letter used.

8. What three losses occur in a transformer? How may each be minimized? What is the relation between the primary loss and the secondary loss?

9. Explain the relative advantages and disadvantages of the "shell" and "core" type transformers. Sketch each type.

10. Explain the construction and advantages of the "cruciform core" type of transformer.

11. What four advantages are obtained from filling transformer cases with oil?

12. What five methods are employed for cooling transformers? What methods are most commonly employed?

13. In distributing power in cities, which plan is considered preferable: a large number of small transformers with short secondary mains, or a few large transformers with long secondary mains? Why?

14. Into how many sections are the primary and secondary windings of commercial transformers divided? What advantages are obtained by this subdivision? State the various combinations of e.m.f. and current that may be obtained.

15. What are the advantages of grounding the secondary winding of a transformer? Where should it be grounded? Sketch.

TRANSFORMERS

TRANSFORMER VECTOR DIAGRAMS

A vector diagram gives a clear picture of the performance of a transformer under various conditions of load.

The elementary relations between voltages, flux and current in an ideal transformer without load will first be considered. By an ideal transformer is meant one which has no resistance in its windings and no losses in its core. Fig. 704 represents the various forces in such a transformer.

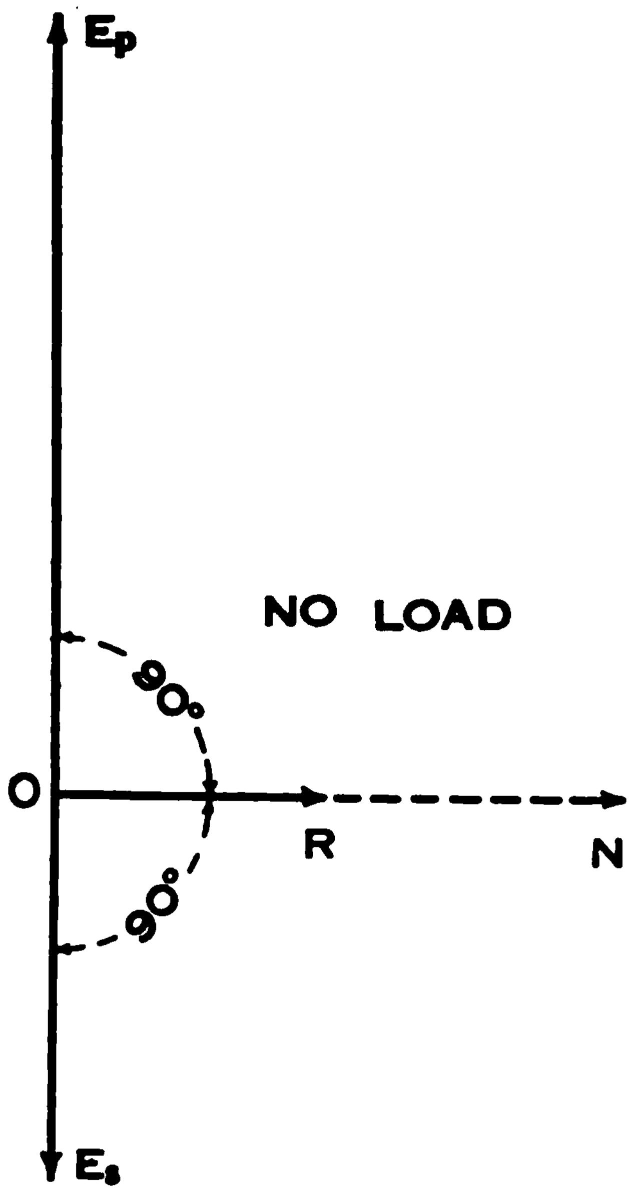


FIG. 704.—Relation between primary current, magnetic flux, impressed voltage and induced voltage in an ideal transformer.

This vector is based upon two fundamental facts:

First: The magnetic flux is always in phase with the current which produces it. Thus, if a direct current is admitted to a magnetizing coil surrounding a soft iron core, the magnetic flux starts from zero with the current. When the current rises to full strength the magnetic flux accompanies it to a maximum value. If the current is lowered to zero, the magnetic flux also falls to zero. If the current is reversed and raised to full strength in an opposite direction, the magnetic flux accompanies it in reversed order. Therefore, if the line *O-R* represents a current in a coil, the line *O-N* in the same direction may represent the flux produced by that current.

Second: Every induced e.m.f. lags 90° behind the flux which, in its variations, induces it. Thus there will be induced in any winding upon an iron core, an e.m.f., *O-Es*, which will lag 90° in phase behind the flux *O-N*. This is because with an alternating current and flux the point of maximum induced e.m.f. will

coincide with the point of zero flux, for the flux is then varying most rapidly, while the point of zero induced e.m.f. will coincide with that of maximum flux, for the flux is then varying most slowly.

The applied e.m.f. will be in the direction *O-Ep*, behind which the magnetizing current will lag 90°. This will be evident from a consideration of Fig. 705, which represents the relations between the current, counter e.m.f. and impressed e.m.f. in the primary of a commercial transformer winding without secondary load. Here it will be observed that the induced or counter e.m.f., *C-B*, is practically in direct opposition to the impressed e.m.f., *A-C*, the slight discrepancy being due to *A-B*, which is a measure of the e.m.f. necessary to overcome the actual losses of such a transformer. As Fig. 704 pictures an ideal transformer having no losses, the line *O-Ep*, showing the impressed e.m.f., will be squarely at right angles to *O-R*, for the current will lag 90° behind the applied e.m.f. under such conditions.

The relative magnitude and direction of four forces are thus shown in Fig. 704.

First: *O-Ep*; the e.m.f. applied to the primary.

Second: *O-R*; the magnetizing current producing — both 90° behind *O-Ep*.

Third: *O-N*; the magnetic flux in phase with it — both 90° behind *O-Ep*.

Fourth: *O-Es*; the e.m.f. induced in either primary or secondary or both, due to the variation of the flux *O-N*.

Next consider the effect of placing a non-inductive load upon the transformer under consideration, Fig. 706. The voltage induced in the secondary *S* is shown in Fig. 707 as *O-Es*, while the magnetizing current *O-M* and the magnetic flux *O-N* are the same as before. The secondary load will take a current *O-Is*, and as the load is non-inductive it will be in phase with the second-

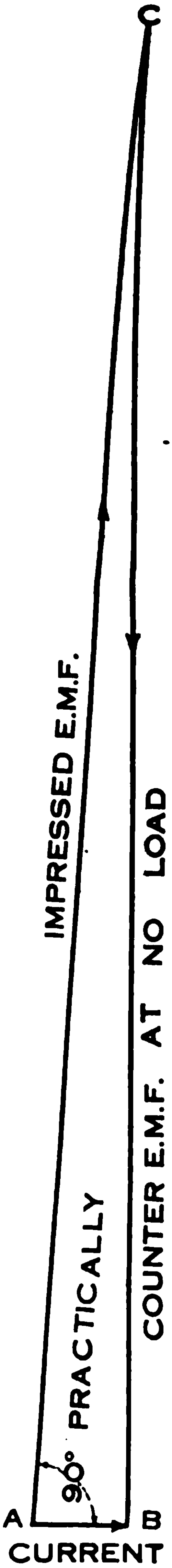


Fig. 705.

ary voltage *O-Es*. To supply this secondary current the primary must take in a current *O-A*, 180° out of phase with the secondary current *Is*, that it may offset the tendency of the secondary current to reduce the flux in the core. This brings it in phase with the applied voltage as the secondary current is in phase with the induced voltage. The actual current flowing in the primary will now be the vector sum of the magnetizing component *O-M*, which is wattless, and the load component *O-A*, which is of real energy value. The sum of these two components is obviously the line *O-B*, which represents the total primary current. *O-B* does not deviate from the primary voltage *O-Ep* in practice nearly so much as the diagram would indicate, but the angle is here exaggerated for the purpose of emphasizing the magnetizing current *O-M*.

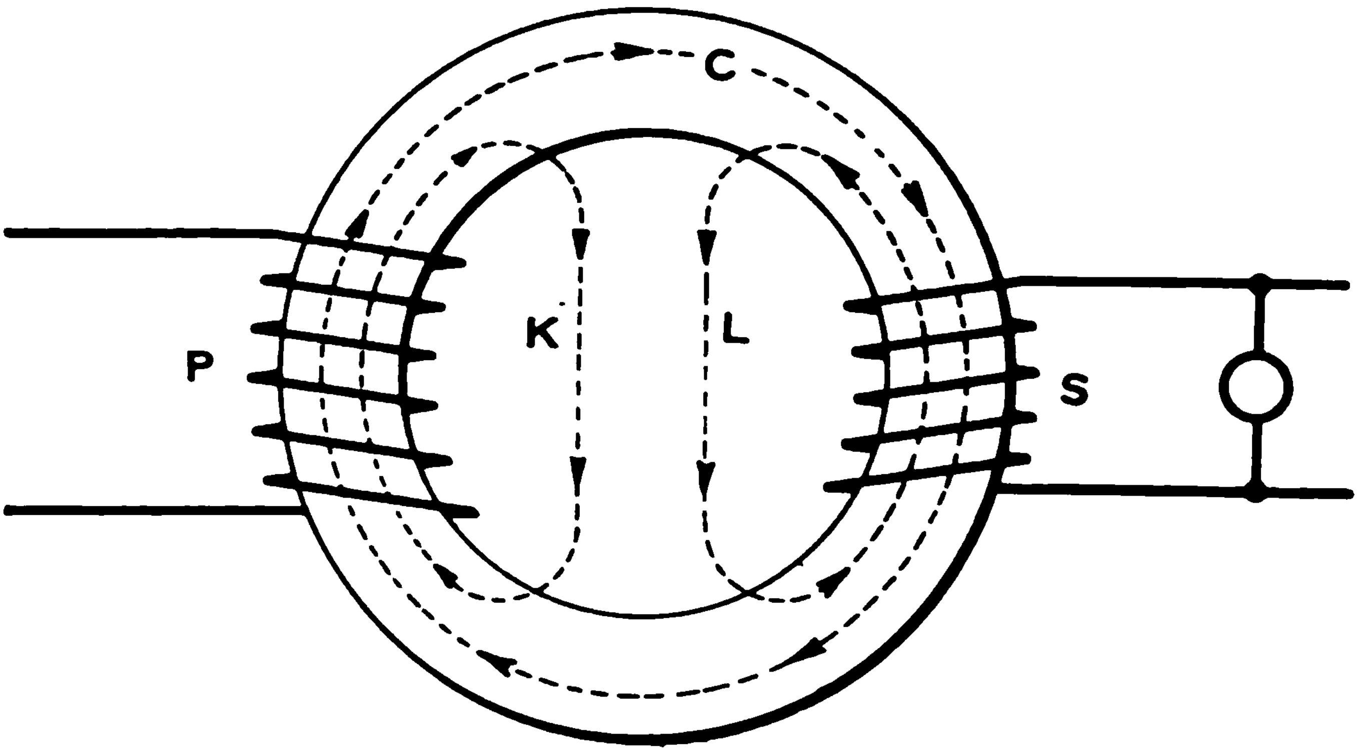


FIG. 706.—Illustrating leakage flux which brings about inductive drop.

Next consider the application of an inductive load to the secondary of the transformer in place of a non-inductive load. The vector diagram will now take the form of Fig. 708. Here *O-M* and *O-N* represent magnetizing current and flux as before. *O-Es* represents the secondary voltage as before, lagging 90° behind the flux. *O-Is* represents the secondary load current lagging behind the secondary voltage by the angle Φ. To supply this secondary load the primary must take a load component of current *O-A*, diametrically opposed to the secondary current. As the magnetizing current is still *O-M*, the vector sum of these two components gives the total primary current *O-B*.

The angle of lag between the load component of the primary current and the applied voltage is Φ', which is the same as the secondary angle of lag Φ. The primary angle of lag, as far as the total current is concerned, however, is increased to Φ'', this increase being due to the distorting effect of the magnetizing current. Again, in practice this apparent discrepancy between Φ' and Φ'' is not nearly so great as pictured.

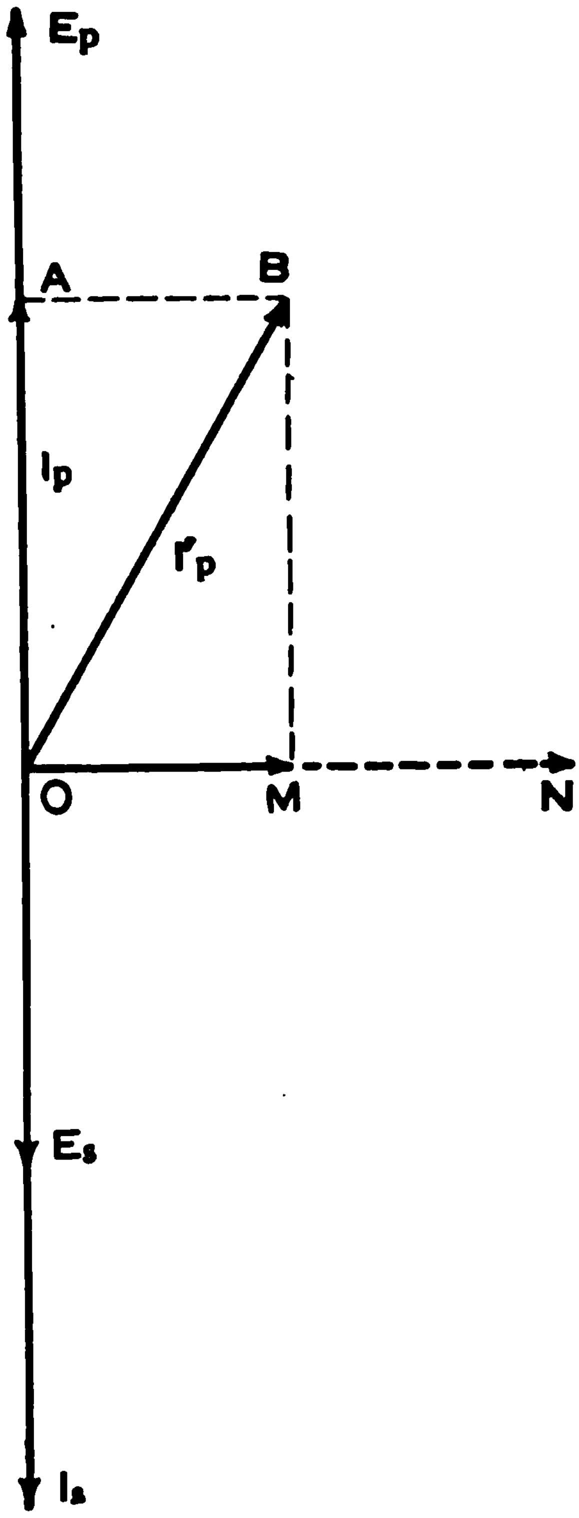


FIG. 707.—Relation existing between magnetic flux, total primary current, secondary current, primary impressed voltage and secondary induced voltage in an ideal transformer with a non-inductive load.

The complete vector for a commercial transformer, in which all of the losses in the core and windings are taken into account, is shown in Fig. 709. While it is not possible to actually make such a vector from observed data, nevertheless the relations of the various forces encountered in actual practice are very clearly shown by such a diagram.

This vector represents an inductive load upon a transformer, and *O-N* represents the flux, which links both windings. Referring to Fig. 706, it will be observed that when a transformer is loaded the flux is broken up into three parts: **First,** that portion *C*, which links both windings; **second,** the reaction of the load current in the secondary winding diverts a portion of the primary flux *K*, so that it leaks across between the two windings and embraces the primary winding only; **third,** the counter magneto-motive-force of the secondary also tends to establish a leakage flux *L*, which would link the secondary winding only. It will be remembered that in actual practice the primary and secondary windings are not on opposite legs of the core as here pictured, but portions of both occupy the same leg, nevertheless there is always some leakable flux between them.

The current required to oscillate the flux, which has been previously called the magnetizing current, must now be increased by an amount necessary to supply the eddy current and hysteresis losses in the iron. The total amount required for this purpose is represented in Fig. 709 by the line *O-P* and is called the "**exciting current.**" This eventually becomes the **exciting component** of the total primary current. Now this exciting current is resolved into two components: *O-M*, the magnetizing component, which is wattless, and therefore 90° away from the induced e.m.f. and in phase with the flux, and the energy component *M-P*, which is in phase with the induced e.m.f. in primary and secondary and is therefore of energy value. It is this component which supplies the core losses. The secondary current lags behind the e.m.f. delivered by the secondary *O-T* by the angle Φ. The e.m.f. delivered by the secondary *O-T* is less than the e.m.f. generated in the secondary *O-Es* by the ohmic and inductive drop *Es-T* in the secondary. Now as the ohmic drop in the secondary is of real energy value it will be in phase with the secondary current as shown. Thus *Es-A* must be drawn parallel with *O-Is*, while the inductive drop *A-T* must be 90° from the ohmic drop and current. The ohmic drop in the secondary winding is due to its resistance. The inductive drop is due to the leakage flux *L* in Fig. 706, which links the secondary winding only. Thus in Fig. 710 the secondary e.m.f. *O-Es* is reduced by the impedance drop in the

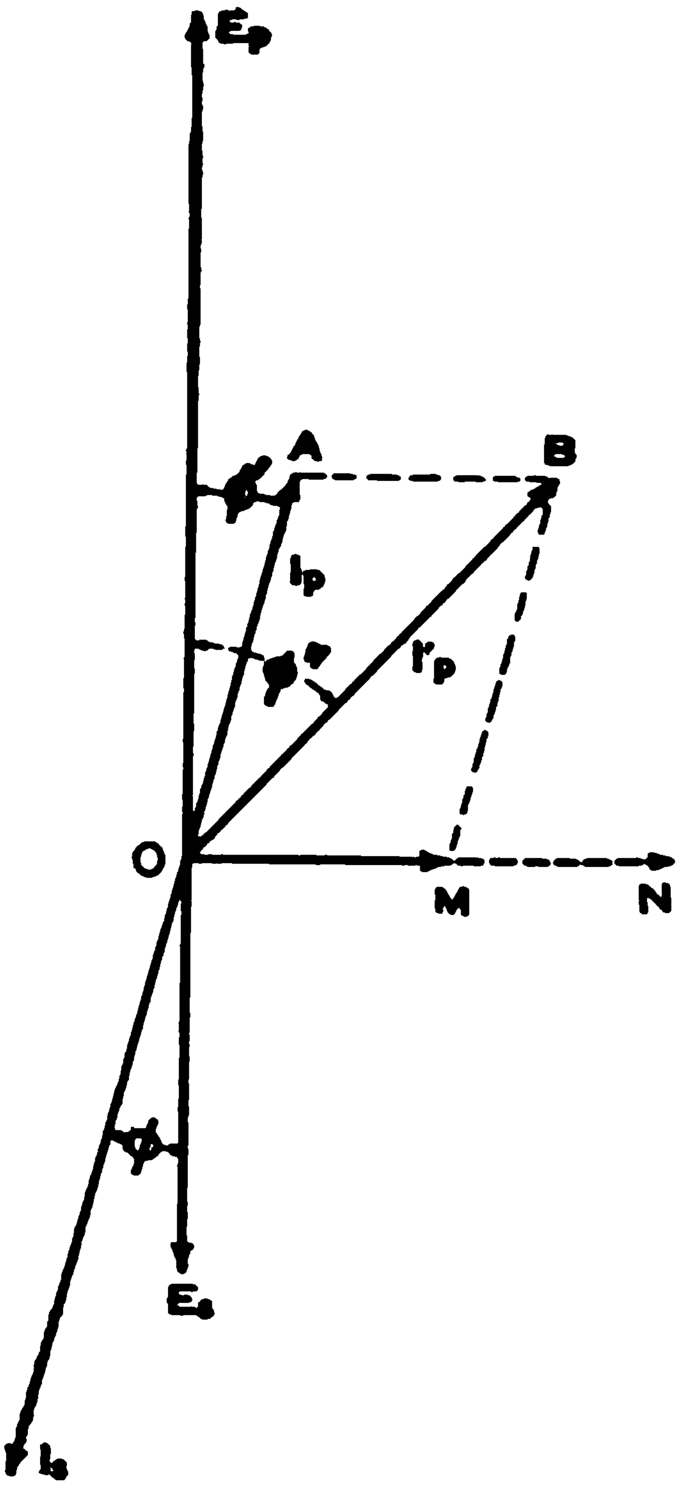


FIG. 708.—Relation existing between magnetic flux, total primary current, secondary current, primary impressed voltage and secondary induced voltage in an ideal transformer with an inductive load.

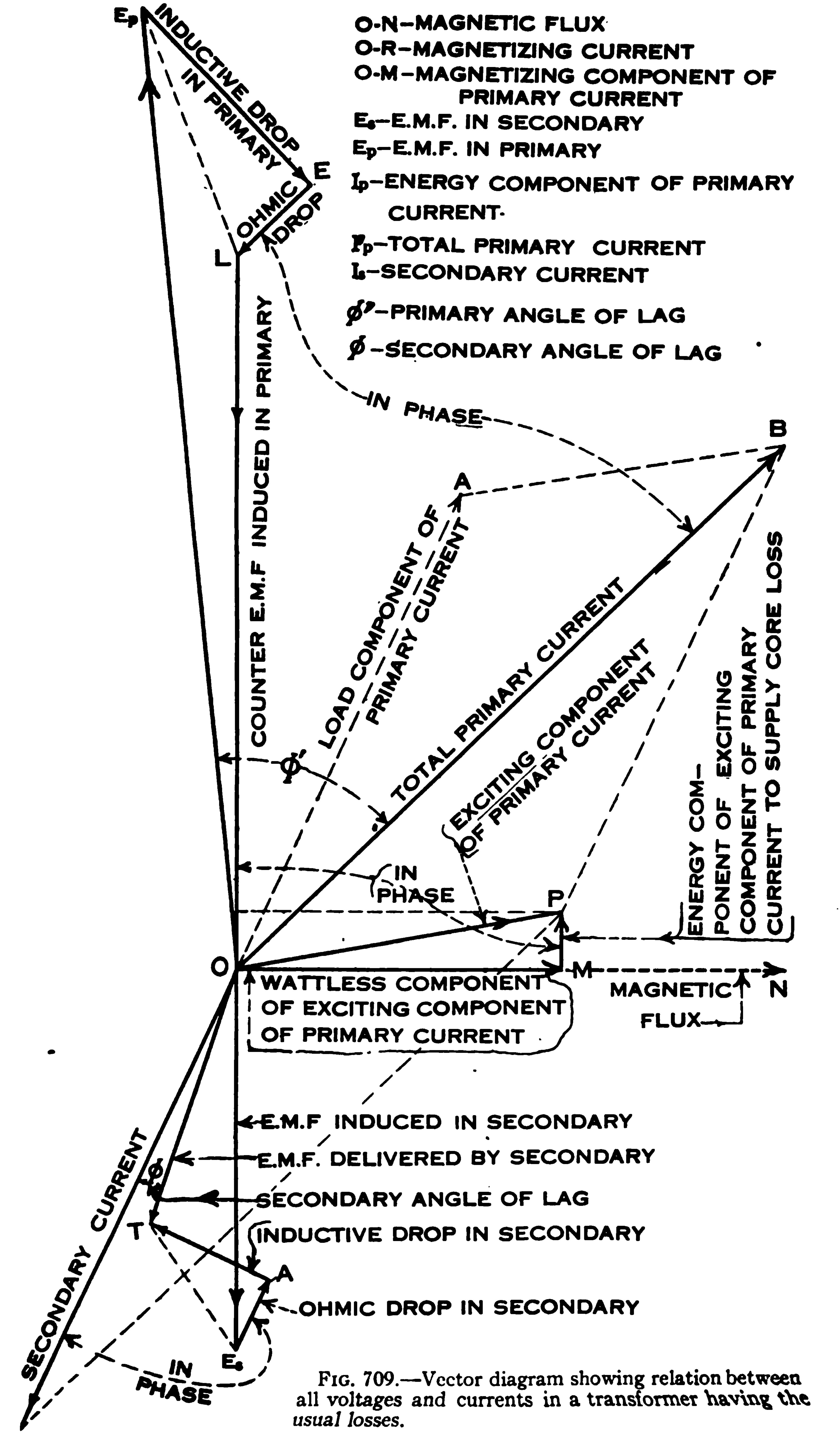


FIG. 709.—Vector diagram showing relation between all voltages and currents in a transformer having the *usual losses.*

secondary, amounting to *Es-T*, which gives a net delivered e.m.f. *O-T*.

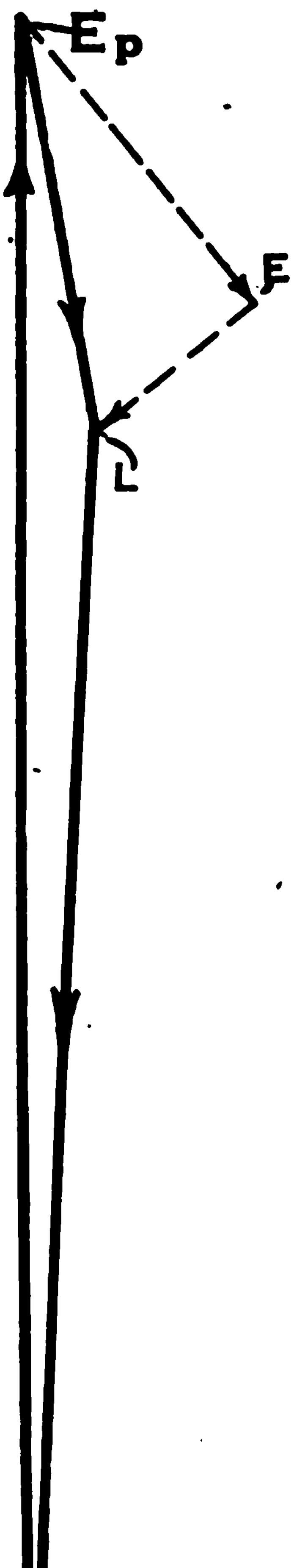


FIG. 711.—Illustrating how the impressed e.m.f. is reduced by the impedance drop to a certain value of counter e.m.f.

The primary will take a current sufficient to supply the secondary load and the exciting current. The load component of the primary will be *O-A*, which is diametrically opposite to the secondary current, *O-Is*. The exciting component is *O-P*. The total primary current will be the vector sum of the *O-A* and *O-P*, which is *O-B*. The primary voltage which must be applied is *O-Ep*. When the transformer is loaded, this is resolved into three parts; first, the inductive drop *Ep-E*. This drop is due to the leakage flux *K*, Fig. 706, which links the primary winding only. Added to this, and displaced 90° in phase therefrom, is the ohmic drop due to the resistance of the primary *E-L*. As in the case of the secondary, the primary's ohmic drop will be in phase with the total primary current *O-B*. Thus the direction of the line *E-L* is established; it is parallel to *O-B*. Perpendicular to this line, the inductive drop line *Ep-E* must be constructed. The remainder of the applied primary voltage represents the counter e.m.f. and is shown by the line *L-O*, perpendicular to the flux *O-N*. The primary angle of lag is evidently Φ', which represents the phase relation of the total primary current and the e.m.f. applied to the primary winding.

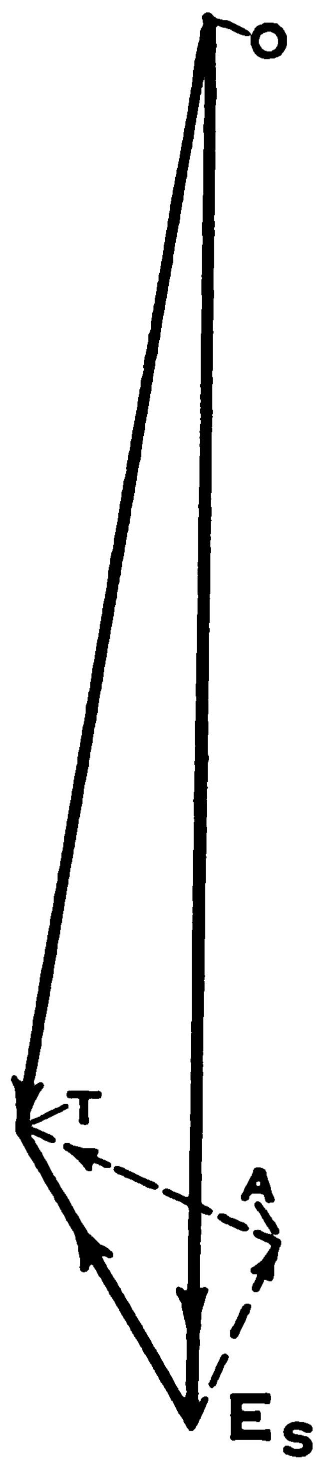


FIG. 710.—Illustrating how generated secondary e.m.f. is reduced by the impedance drop to the delivered e.m.f.

In Fig. 705, representing the

conditions in the primary of an unloaded transformer, the counter e.m.f. was virtually equal to the impressed e.m.f., but as soon as the load is applied the primary e.m.f. *O-Ep*, Fig. 711, is broken up into an impedance drop *Ep-L*, consisting of the inductive drop *Ep-E* and an ohmic drop *E-L*, and the remainder *L-O* represents counter e.m.f. which is therefore effective in transferring energy to the secondary.

The counter e.m.f. in the primary *O-L*, and the delivered e.m.f. by the secondary *O-T*, are caused by the flux *C* only, Fig. 706, which links both primary and secondary windings.

SECTION XV CHAPTER III

TRANSFORMERS

TRANSFORMER VECTOR DIAGRAMS

1. Show by vector diagram the phase relation between the magnetizing current, the magnetic flux, the voltage impressed on the primary and the voltage induced in both the primary and secondary of an ideal transformer.

2. (*a*) What is the phase relation between the current in the primary and the current in the secondary of a transformer?

(*b*) What is the phase relation between the e.m.f. impressed on the primary and the e.m.f. induced in the secondary?

(*c*) What is the phase relation between the e.m.f. induced in the primary and the e.m.f. induced in secondary?

3. Sketch an e.m.f. triangle for a transformer showing the phase relation between the current, counter-e.m.f. and impressed e.m.f. Explain why this phase relation exists.

4. Sketch a vector diagram for an ideal transformer with a non-inductive load.

5. Sketch a vector diagram for an ideal transformer with an inductive load.

TRANSFORMERS

THE ACTUAL CONSTRUCTION OF A TRANSFORMER VECTOR DIAGRAM

In practice it is not possible to separate the impedances of the primary and secondary windings as pictured in Fig. 709, nor to represent the currents and voltages in the two windings to the same scale. The correct way to picture the facts is to draw the various vectors as though the transformer had a one-to-one ratio. At the same time the resistance of the two windings, and their reactances and total impedances, are reduced to the equivalent of one winding, which enables the actual results to be clearly represented.

A complete vector will now be constructed for a one K.V.A. 60-cycle transformer having a 2,200 to 220 voltage ratio. Lay

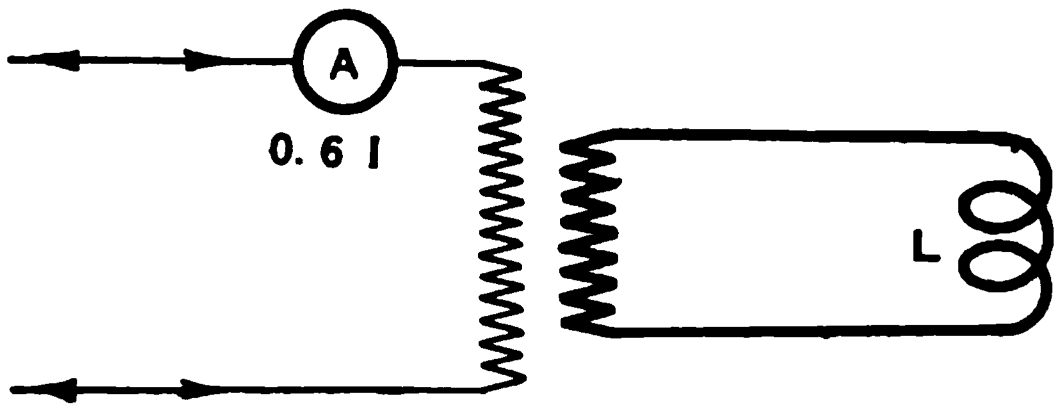


FIG. 713.—Transformer connected to inductive load.

off the horizontal line *M-N*, Fig. 712, and erect at *O*, perpendicular thereto, the line *O-F*, to scale, representing the primary volts applied, *Ep*. As this must be expressed in terms of low-tension voltage to give the equivalent of a one-to-one ratio, the line *O-F* will equal *Ep* divided by 10.

Next construct the line *O-G*, diametrically opposite to *O-F*, representing the secondary voltage generated at no load. As this is to full scale this line will be of the same length as that representing the primary applied voltage.

The transformer may now be loaded with an inductive load *L*, Fig. 713, involving an angle of lag of, say, 30°. Let this load be sufficient to call for a primary intake of 0.6 ampere as shown. *O-A* may now be constructed with an angle of 30°, Φ, behind the

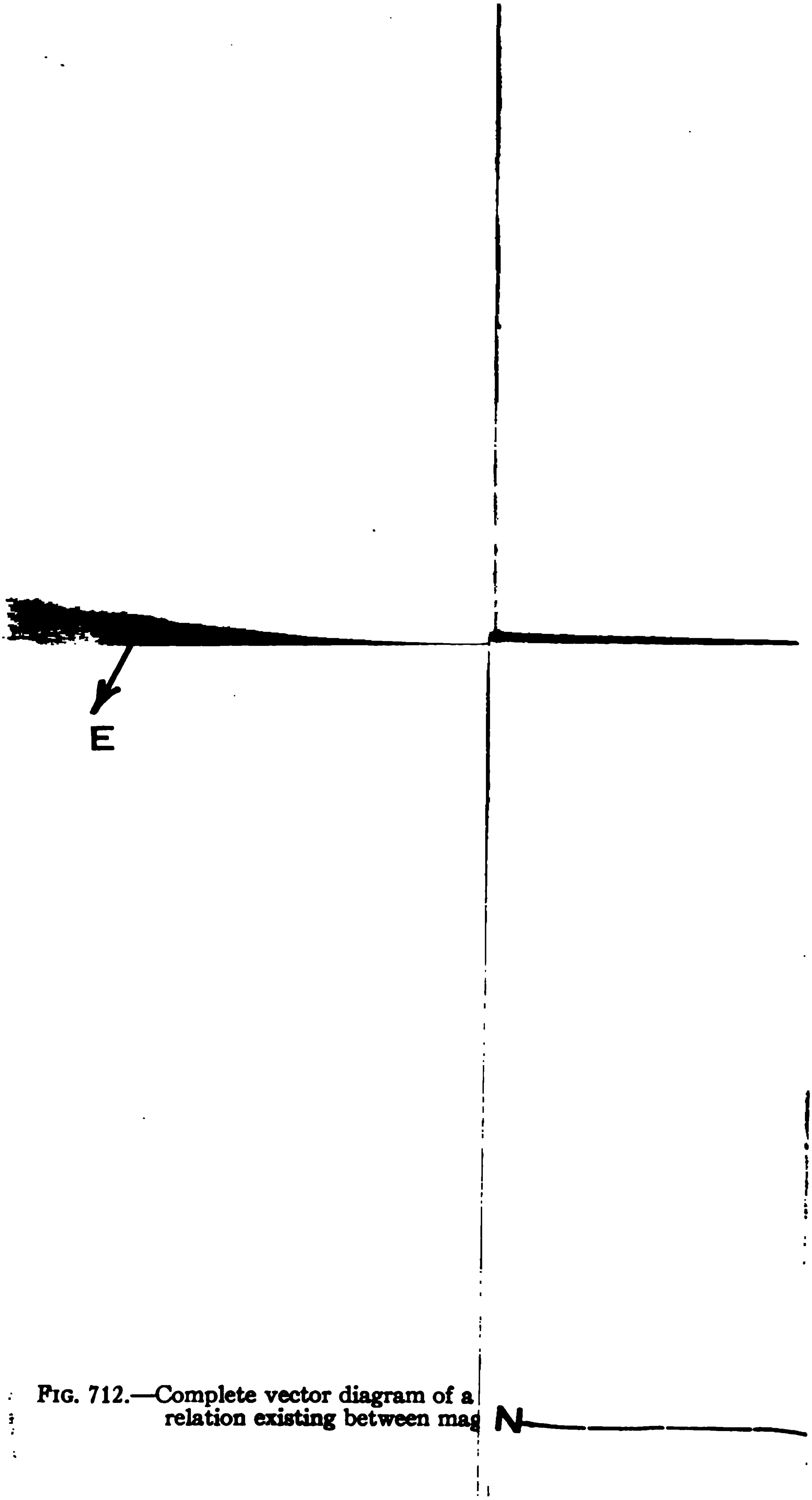


FIG. 712.—Complete vector diagram of a
relation existing between mag

$$\sqrt{OB^2 - CB^2} = Mi = \sqrt{0.25^2 - 0.136^2} = 0.2 \text{ ampere.}$$

applied primary voltage *O-F*, and for the time being *O-A* will be of indefinite length, for it simply represents the direction of the load component of the primary current, and this will be later increased by the exciting current.

The exciting current should now be measured by putting an ammeter in series with the high-tension winding and connecting it to the 2,200-volt source of supply with the secondary on open

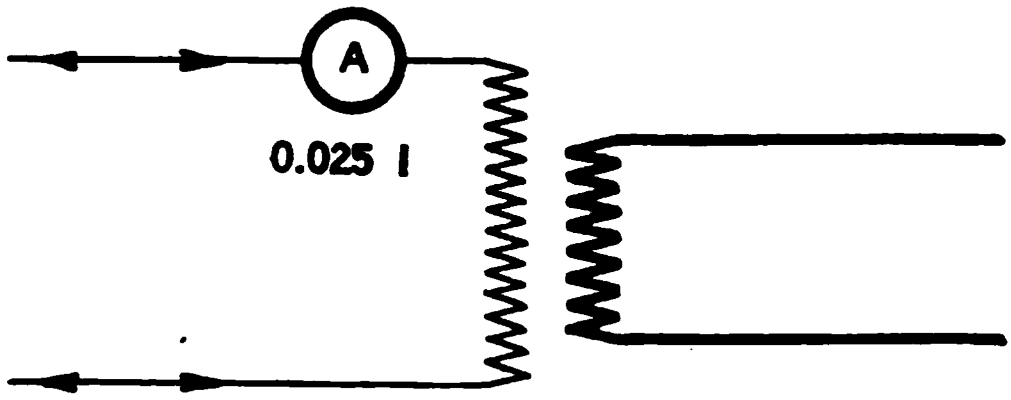


FIG. 714.—Connections for measuring exciting current.

circuit as shown in Fig. 714. Let this current be 0.025 ampere. This must be reduced to low-tension terms by multiplying by 10, which gives 0.25 ampere. This current could have been measured just as readily on the low-tension side, for the exciting current can be furnished through either winding.

The core loss should next be measured by connecting a wattmeter on the low-tension side and supplying the loss from a 220-volt source with the high-tension side open as shown in

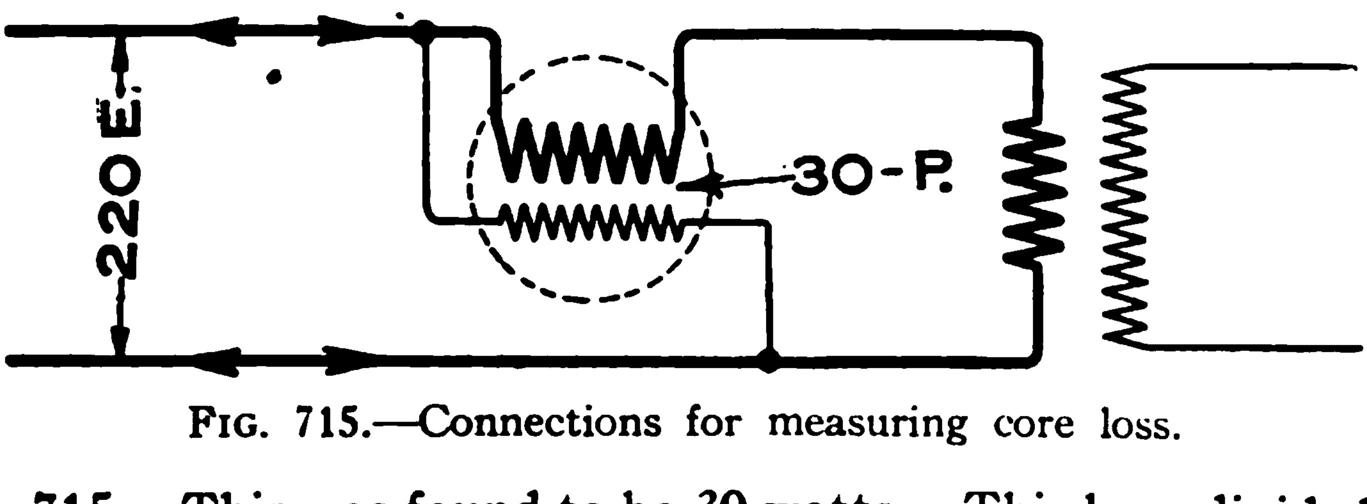


FIG. 715.—Connections for measuring core loss.

Fig. 715. This was found to be 30 watts. This loss, divided by the applied voltage, will give the energy component of the exciting current; thus, $\frac{P}{E} = I = \frac{30}{220} = 0.136$ ampere. The current triangle for the excitation of the transformer is shown in Fig. 716. Here *O-B* represents the total exciting current and *C-B* is the energy component thereof: Obviously *O-C* the wattless or magnetizing component will be:

$$\sqrt{OB^2 - CB^2} = Mi = \sqrt{0.25^2 - 0.136^2} = 0.2 \text{ ampere.}$$

Having the three sides of this triangle in low-tension terms, it should now be constructed as *O-C-B*, in Fig. 711. *B-D* may now be drawn indefinitely long and parallel to *O-A*. If the intake for the primary of the transformer is to be limited to 0.6 ampere, then this drawn to low-tension scale by multiplying by 10 will give *O-D*, 6 units long. The parallelogram for the primary may then be completed, *O-B-D-A*. It is thus evident that *O-B* will represent the exciting component and *O-A* the load component of the primary current, while *O-D* represents the total primary current. The vector for the secondary current *O-E* may now be laid off equal in length and diametrically opposite *O-A*. If *O-D* in low-tension terms represented a total primary intake of 6 amperes, then *O-A*, the load component, will represent approximately 5.8 amperes. *O-E* should therefore be made 5.8 units long.

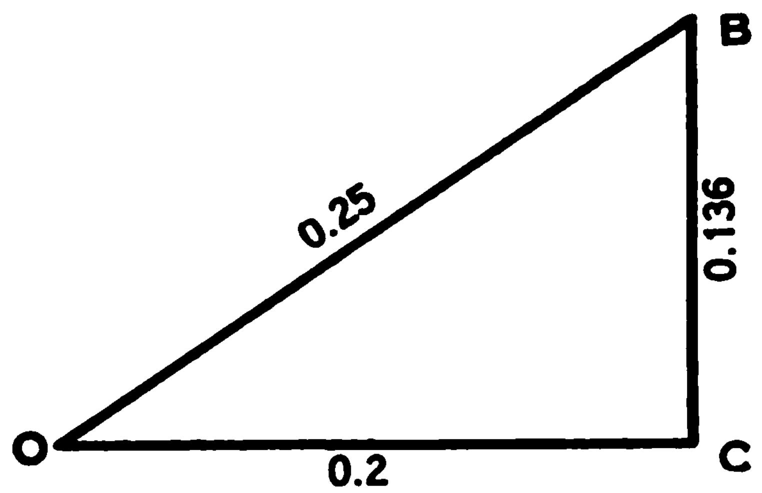


FIG. 716.

Next, the resistance of the primary and secondary windings should be measured separately and combined in terms of the low-tension winding. Connect the low-tension winding on a D. C. source of supply with a voltmeter across the terminals and an ammeter and a rheostat in series with the source, Fig. 717. The high-tension winding should be short circuited to prevent the inductive kick from injuring the voltmeter if the low-tension circuit is suddenly opened.

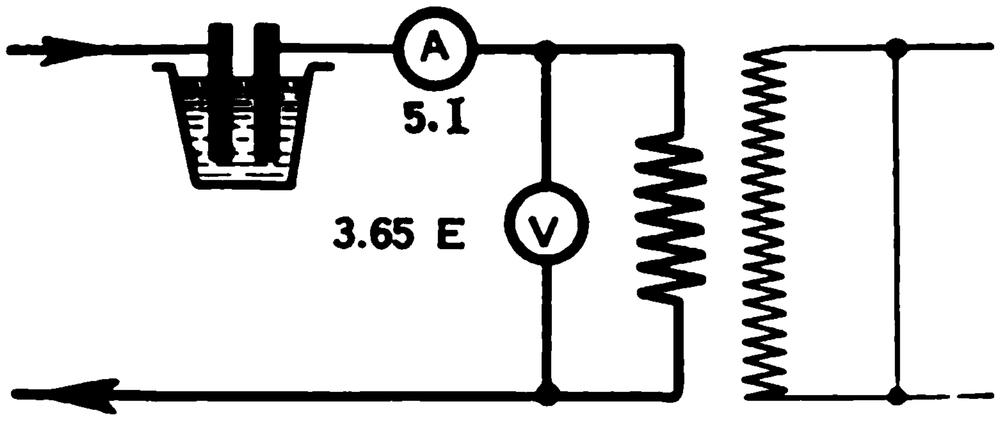


FIG. 717.—Measurement of resistance of transformer windings.

With a current of 5 amperes the fall in potential was found to be 3.65 volts. The resistance of this winding is therefore:

$$\frac{E}{I} = R = \frac{3.65}{5} = 0.729 \text{ ohm.}$$

The resistance of the high-tension winding should be measured in a similar way, the low-tension winding being meanwhile short circuited. The readings obtained were 40.75 volts drop with a current of 0.5 ampere. As

$$\frac{E}{I} = R = \frac{40.75}{0.5} = 81.5 \text{ ohms.}$$

Now the resistance of the two windings varies directly as the square of the ratio of turns. Thus to reduce the resistance of the high-tension to low-tension terms:

$$\frac{\text{Res. H.T.}}{\text{Sq. of ratio turns}} = \text{H.T. resistance in terms of low tension.}$$

$$\frac{81.5}{10^2} = 0.815 \text{ ohm.}$$

The resistance of the high-tension and low-tension windings are in effect in series, for if these windings had a one-to-one ratio

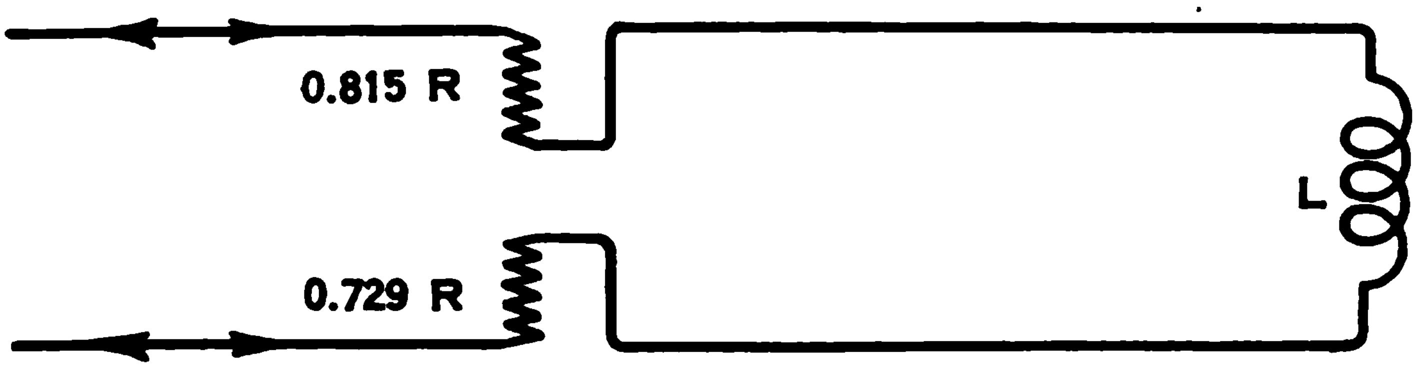


FIG. 718.—Resistance of high-tension and low-tension windings are virtually in series.

the effect upon the load, as far as resistance was concerned, would be as though a winding having the equivalent of 0.815 ohm, Fig. 718, were in series with another winding having 0.729 ohm between the source and the load *L*. The total equivalent resistance of the two windings is therefore $0.815 + 0.729 = 1.544$ ohms. Theoretically these two values should be equal, but, as the high-tension winding is wound outside of the low-tension winding, the length of a mean turn of the former is greater than the latter and consequently its total effective resistance is higher.

The impedance of the transformer must next be measured. To do this the low-tension side is placed on short circuit as shown in Fig. 719 and the high-tension winding is connected upon an A. C. low-tension source in series with a rheostat and an ammeter, with a voltmeter across the winding. The rheostat

should be adjusted until the high-tension winding receives approximately its full-rated current. In this case it was given 0.455 ampere, and the observed drop was 87 volts. The actual current here employed to find the impedance is not important,

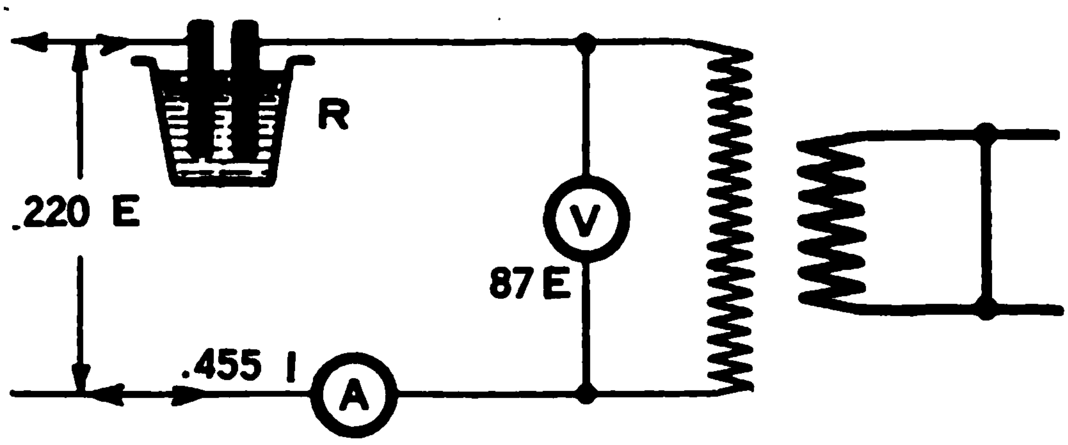


FIG. 719.—Measurement of transformer impedance.

for within the limits of saturation the impedance is independent of the current.

The total equivalent impedance of the two windings is found by dividing this drop by the current:

$$\text{Thus} \qquad \frac{Pe}{Pi} = Z = \frac{87}{0.455} = 191 \text{ ohms.}$$

Pe = drop across high-tension winding.
Pi = current in high-tension winding.
Z = total equivalent impedance of transformer in terms of high-tension winding.

To reduce to low-tension terms the impedance must be divided by the square of the ratio of the turns. As the ratio is 10 to 1,

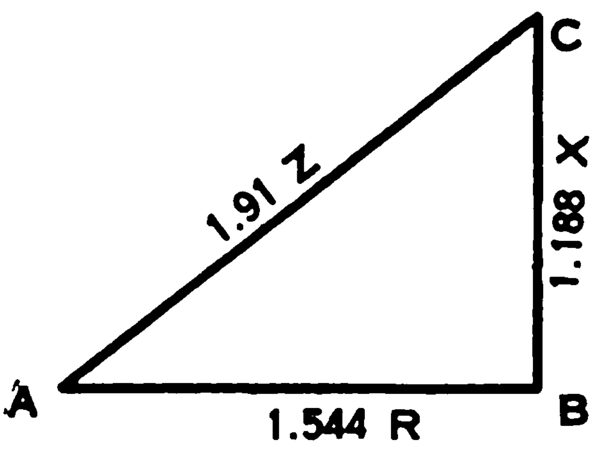


FIG. 720.

$$\frac{\text{Impedance of } H.T.}{\text{Sq. of ratio of turns}} = H.T. \text{ impedance in } L.T. \text{ terms}$$

$$\frac{191}{10^2} = 1.91 \text{ ohms.}$$

The equivalent total reactance of the transformer should next be computed. If, in Fig. 720, A-C = 1.91 ohms impedance, and A-B = 1.544 ohms resistance, then the equivalent reactance will be:

$$X = \sqrt{Z^2 - R^2} = \sqrt{1.91^2 - 1.544^2} = 1.188 \text{ ohms.}$$

The impedance of a transformer operates to reduce the secondary voltage. The secondary current of 5.8 amperes flowing through the equivalent total resistance of the transformer, 1.544 ohms, will fall in potential $R \times I = E$ volts $= 1.544 \times 5.8 = 9$ volts. This voltage drop should be constructed to scale backward from the point G to the point H, Fig. 712, in a direction parallel to the line O-E, for the ohmic drop is in phase with the current in the secondary winding. This current also encounters the reactance of the secondary, and the reactive drop will be $X \times I = E = 1.88 \times 5.8 = 6.75$ volts. This drop must now be constructed to scale from the point H to K, 90° away from the ohmic drop G-H. The total loss due to the impedance of the transformer is therefore G-K, and the delivered volts at full load will be reduced from the no-load voltage O-G to O-K. The secondary angle of lag will obviously be Φs. The total primary angle of lag will be Φp, which exceeds the secondary angle by a certain amount due to the exciting current.

It will be noted that the delivered voltage of the secondary, O-K, is slightly out of phase with the no-load voltage O-G. This is an incident of the particular power factor which the load was assumed to possess. Should the secondary load have involved a greater angle of lag, the triangle G-K-H would have tilted to the right in order that G-H might parallel O-E. At a certain particular angle it is evident that O-K would have coincided exactly in phase with O-G. As the power factor of the secondary load varies, it is evident that the triangle G-H-K will swing one way or the other on the pivot G and thus vary to a small degree the phase angle of the full-load voltage with respect to the no-load voltage. The exact relation, however, is of no particular importance.

This vector emphasizes three things very clearly:

First: That the exciting current to supply the core losses and keep the flux alternating is a very small part of the load current in the transformer.

Second: That the total impedance of the windings makes a very slight reduction in the no-load voltage at full load. The actual e.m.f. observed at full load in this case was 210 volts.

Third: While the core losses increase the primary current for a

given secondary load, the resistance and impedance of the two windings reduce the delivered secondary full-load voltage for a given applied primary voltage.

SECTION XV CHAPTER IV

TRANSFORMERS

THE ACTUAL CONSTRUCTION OF A TRANSFORMER VECTOR DIAGRAM

1. Sketch the actual vector diagram for a commercial transformer with a non-inductive secondary load. State in detail the process of taking the data for this diagram, and sketch connections for each test which must be made.

TRANSFORMERS

TRANSFORMER TESTING

All manufacturers subject their transformers to a variety of tests to determine the losses, efficiency and regulation. The temperature rise under working conditions is also determined. Most operating power companies also test their transformers to determine the condition of insulation and to know in advance the probability of successful operation.

Double Potential Test

Before leaving the factory every transformer is subjected to the double-voltage or over-potential test, Fig. 721. If each of the two sections of the low-tension winding is designed for 110

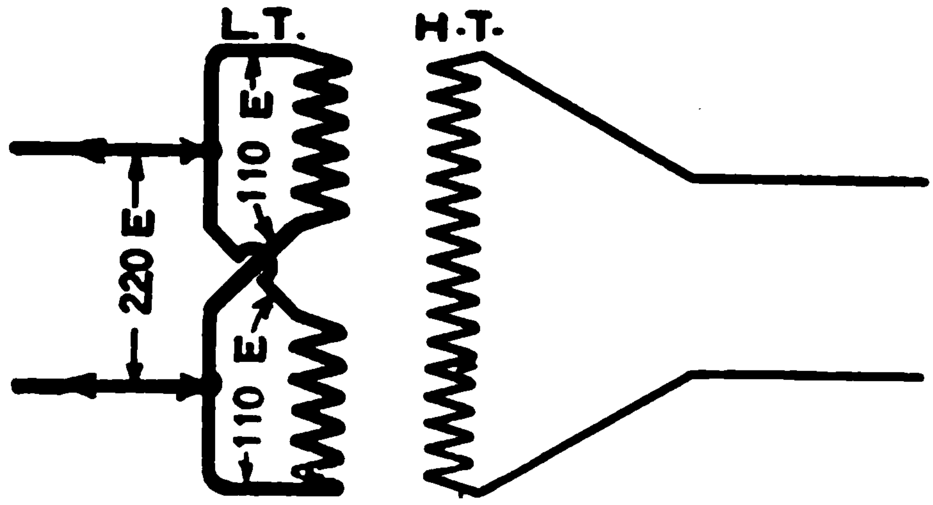


FIG. 721.—Double-voltage transformer test.

volts, they are connected in parallel and 220 volts is applied for five seconds. This tests the insulation of the winding between adjacent convolutions. The high-tension winding is meanwhile left open. As double voltage is applied to the low-tension winding, double voltage is also induced in the high-tension winding. While the insulation of a transformer may give no trouble at normal voltage, it may break down at an applied voltage in excess of normal such as would be caused by a line surge. The ability to withstand such a surge depends upon the insulation between turns and layers. If normal frequency were used to make this test, the exciting current would be excessive. To prevent this excessive current the test should be made with increased frequency. If the frequency is increased in direct

proportion to the voltage, there will be no increase in magnetic density and the exciting current will be approximately the same.

Insulation Test

In order that it may be definitely known that the insulation of the winding is adequate, the insulation or break-down test is applied. From an electrical standpoint, the weakest part of a transformer is its insulation. It is essential, therefore, that any possible defects in the insulation, due to poor material or damage received during process of manufacture, be detected and eliminated before placing the transformer in service. Insulation tests are made on completed transformers for determining the effectiveness of the insulation. This can be determined by actual test only, although a careful mechanical inspection is often of value and will eliminate conditions that might cause a breakdown unless corrected before making the electrical tests. This test, shown in Fig. 722, provides that a current from any convenient A. C. source of low potential be applied to a testing transformer

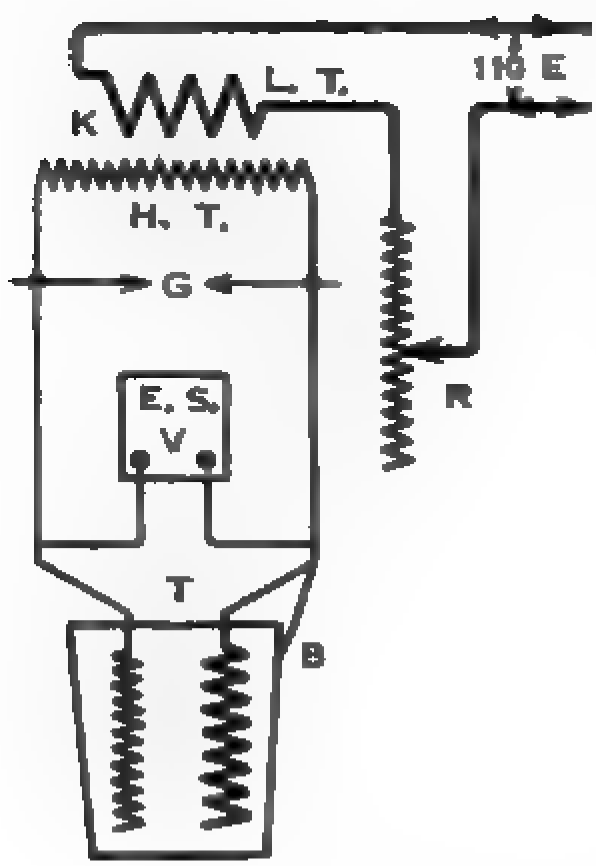


FIG. 722.—Insulation or break-down test.

K, with a rheostat R, in series to limit the voltage applied. The secondary can thus be made to deliver from 10,000 volts up. The transformer T under test has first its low-tension winding and the case connected to one side of the high-tension testing circuit, while the high-tension winding is connected to the other side of the testing circuit. The spark gap G is adjusted to a certain length to prevent too high a voltage being applied. The electro-static voltmeter V indicates the voltage. With these connections the efficiency of the insulation between the high-tension and low-tension windings and between the high-tension winding and the transformer core and case will be

determined The ground *B* is then disconnected from the low-tension side and put on the high-tension side. When the voltage is again applied the insulation between the two windings is again tested, but this time between the low tension and the ground instead of the high tension and the ground.

Load Test

To test a single, small transformer under full-load conditions it may be loaded upon a bank of lamps. Where three transformers of the same size are available which are to be tested simultaneously, they may be tested under full-load conditions without absorbing anything except the losses. This connection

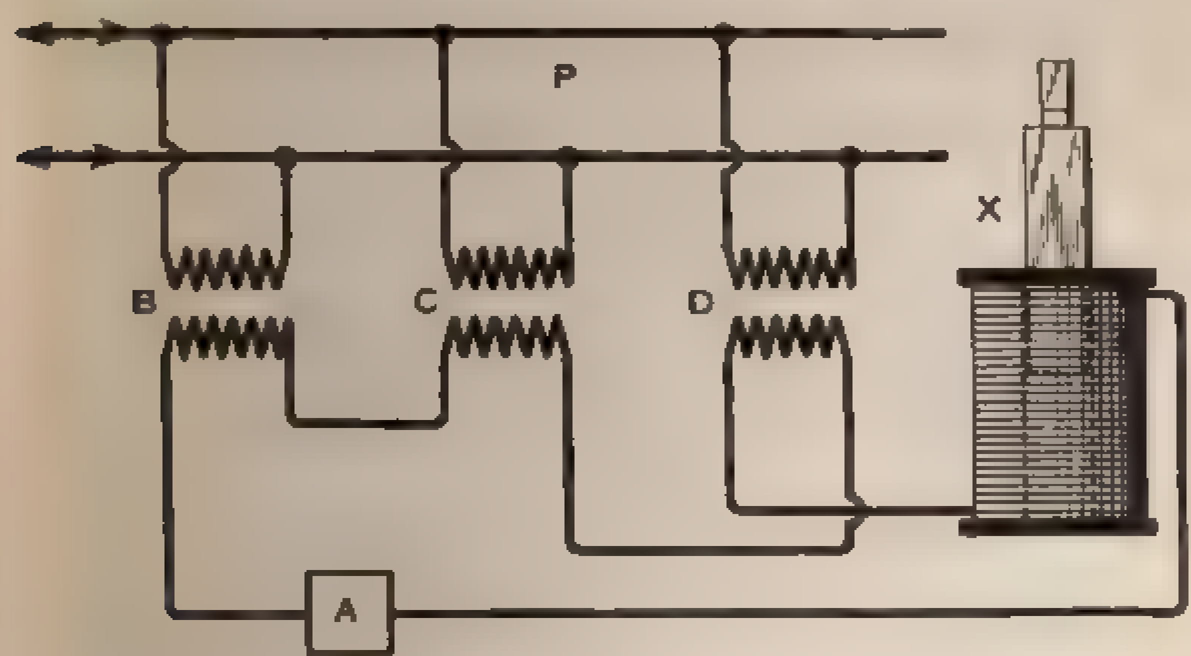


Fig. 723.—Balancing two transformers against each other and circulating full-load current by means of a third transformer

is shown in Fig. 723. Here the high-tension windings of the three transformers are connected in parallel across the primary mains *P* The three low-tension sections are connected in series, but two are arranged so that their e m.fs are bucking each other, while the third furnishes the voltage to circulate the current of the load through all three An adjustable reactance *X* may be employed to adjust the current to the proper value, said current being indicated by the ammeter *A*. The copper losses in all three transformers and the core loss of *B* will be absorbed by the transformer *B* The primaries of *C* and *D* absorb an exciting magnetizing current which includes core losses for *C* and *D* only.

Transformers C and D are connected in opposition and without transformer B would not circulate current but would absorb core losses only. Inserting transformer B as shown causes it to circulate the current without changing conditions in C and D. Thus B supplies copper loss for all three and its own core loss. Transformers for this test must be of the same ratio and also should have approximately the same impedance, otherwise voltages on high side of transformers C and D may be unbalanced or in some cases excessive.

To determine the temperature rise of the transformers operating under the above conditions, X is adjusted to pass about 150% of full-load current. After so operating until no further rise in temperature is observed, this temperature must not be in excess of that specified, usually a rise of 40° C. Some transformers are designed with higher copper and core densities with a permissible rise of 55° C.

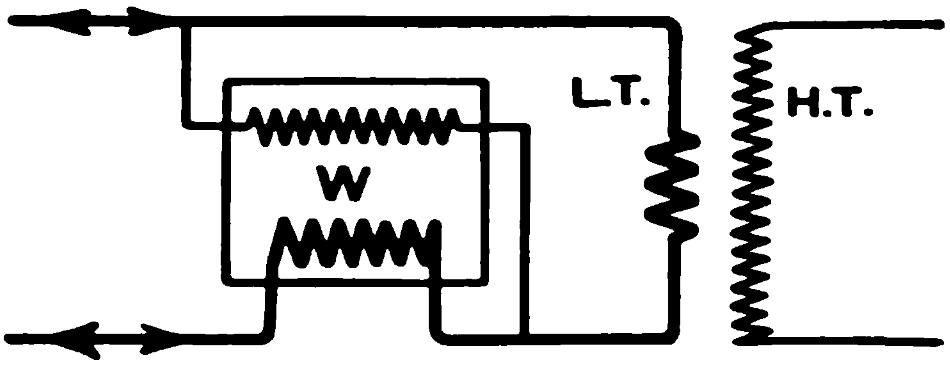


FIG 724.—Connections for measuring core loss in transformer.

A convenient method of ascertaining the temperature indirectly is through a measurement of the resistance of the winding, both before and after the temperature run. Rise in temperature is accompanied by an increase in resistance. It has been found that for each 2.5° C. rise in temperature the resistance of the winding will increase approximately 1%. Thus, if after an interval a 10% increase in resistance were observed, it would indicate a 25° C. rise in the temperature. While this method of determining the temperature is often used, it only gives the average temperature and does not take into account the hot spots and should be checked by actual thermometer readings.

Core-Loss Test

To ascertain the core losses in the iron of transformers a wattmeter is inserted in the low-tension circuit which is connected to its rated low-tension source of supply as in Fig. 724.

The high-tension winding is left open. The wattmeter will indicate the power required for the eddy current and hysteresis losses in the core.

The iron loss is constant for all loads but varies with the frequency. The higher the frequency the less the loss. At first glance this would seem incorrect, but a little consideration will prove it would be the case. Neglecting the resistance of the windings, the current that will flow in an inductive circuit is

$$I = \frac{E}{6.28\,n\,L}$$

Now if the frequency, n, is doubled, it will cause the current to be halved. The eddy currents induced in the core vary as the square of the flux density and as the square of the frequency.

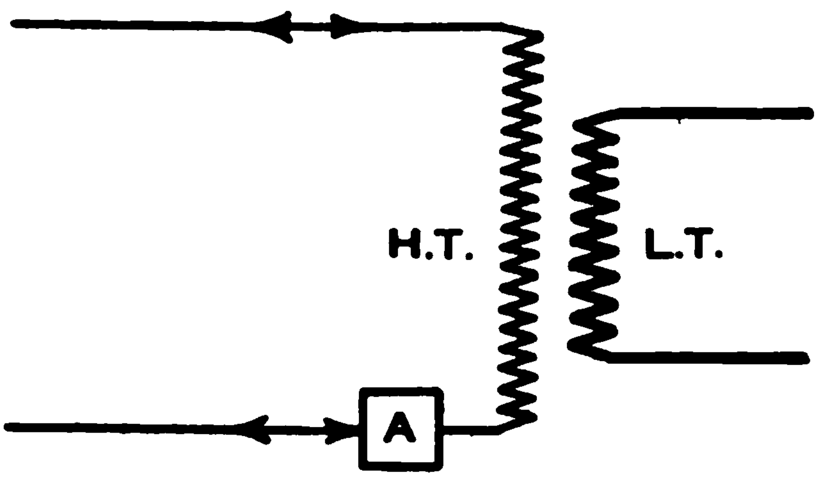


FIG. 725.—Connections for measuring exciting current in transformer.

Therefore, if the current and consequently the flux density are halved and the frequency doubled, the eddy current loss is not affected.

The hysteresis loss varies as the simple frequency and as the 1.6 power of the flux density. Therefore, if the frequency is doubled and the flux density is halved, the actual hysteresis is decreased. Hence the total core loss falls as the frequency rises.

As a result of the foregoing facts it should be noted that a transformer can always be operated at a higher frequency than that for which it was designed, and at a higher frequency will have a somewhat greater capacity.

Exciting-Current Test

The exciting current for a transformer is measured by an ammeter in the high-tension winding which is connected to a

high-tension source as in Fig. 725, with the low-tension winding open. To avoid the necessity for handling high-tension circuits the exciting current could be measured on the low-tension side and reduced to high-tension terms by dividing by the ratio of the transformer.

Copper-Loss Test by Direct Current

The copper loss in a transformer may be measured in two ways—by the direct-current method and by the alternating-current method. To measure the loss by the D. C. method, each winding is in turn connected to a low-tension direct-current source as shown in Fig. 726. A voltmeter should be placed across the winding and an ammeter and rheostat in series therewith. Any convenient current within the rated capacity of the

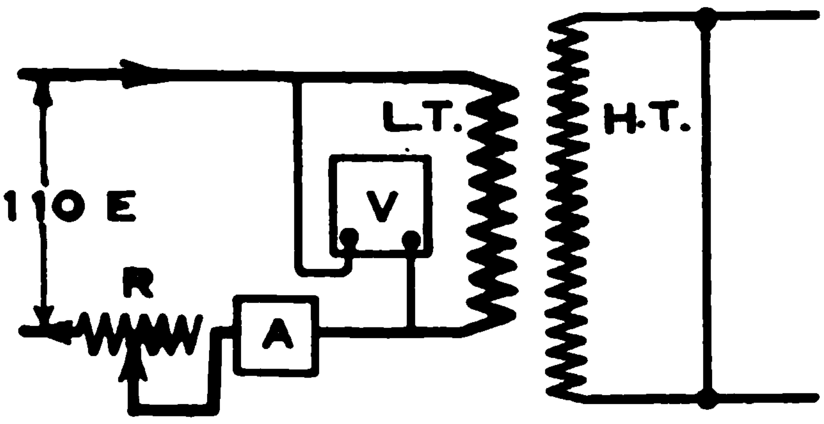


FIG. 726.—Measurement of resistance of transformer winding by direct current.

winding is passed through the circuit and the voltage drop noted. The winding, not being tested, should be short-circuited during the test to reduce the inductive kick on the voltmeter in the winding under test when the circuit thereon is opened. The drop across the terminals divided by the current gives the resistance of the winding in ohms. The square of the full-load rated current for that winding, multiplied by the measured resistance of the winding when hot, is a measure of the copper loss in that winding; $I^2R = P$. The connections to the winding should then be changed and the loss computed for the high-tension winding in the same way. The total copper loss is the sum of the two losses as calculated.

Copper-Loss Test by Alternating Current

To measure the copper loss by the A. C. method, the transformer should be connected as in Fig. 727. The low-tension winding is short circuited, and the high-tension winding is con-

nected to a low-tension source. The rheostat R is adjusted until the ammet r A shows the full-load current in the high-tension winding which will likewise induce a full-load current in the low-tension winding. The voltage drop across the high tension will now be from 3 to 6% of the rated voltage. This drop, divided

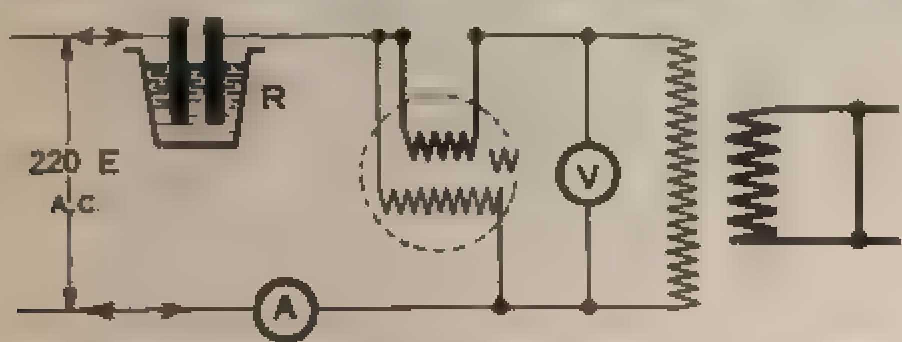


FIG. 727 Measurement of copper loss by A. C. method.

by the current, gives the impedance of the transformer. When the high-tension winding is thus receiving its full-load current the wattmeter W will read approximately the total copper loss for the two windings The indication is not exact, as some core loss is included in this measurement. The amount so included is quite small, however, because the applied voltage is small and

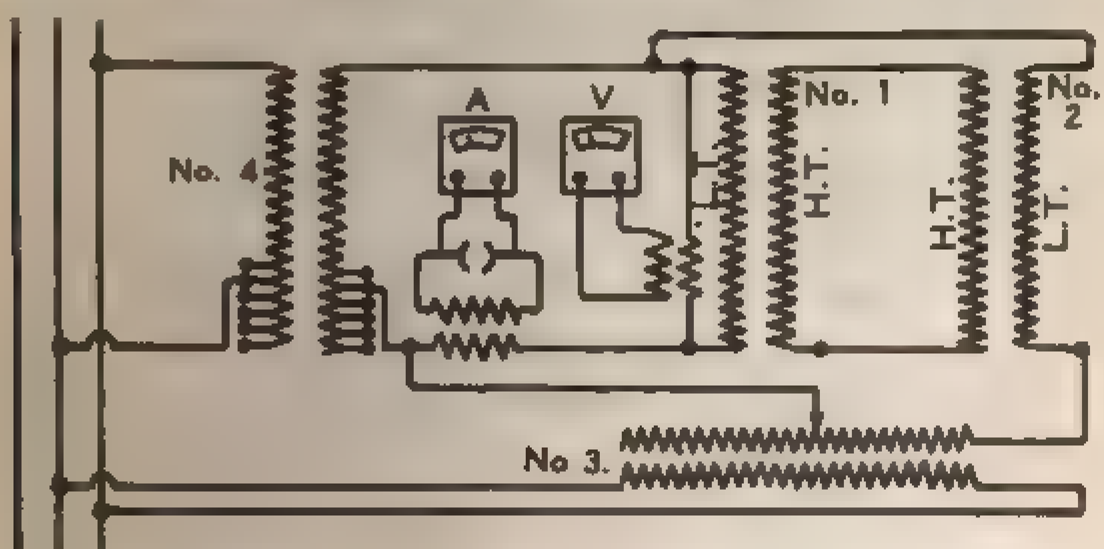


FIG. 728. "Loading-back" test for identical transformers, load current being applied to low-tension winding.

the flux density varies with the applied voltage If it is desired to obtain the copper loss accurately by this method, correction for the core loss may be made as follows. After having read the voltage drop with the secondary short circuited, disconnect the source of supply Then remove the short circuit on the secondary. Then adjust R until the voltmeter V reads the same as it did before The wattmeter W will now read the amount of core loss

which was previously included in the copper loss reading. This may be deducted if desired.

Loading Back Test

Where two large identical transformers are to be tested they may be loaded back upon each other as shown in Fig. 728. Here the high-tension windings of transformer No. 1 and transformer No. 2 are connected in series and in opposition. The low-tension windings will likewise be connected in series with each other and also in series with the secondary of a third transformer, No. 3, having a variable ratio and whose primary is connected across the source of supply. This third transformer furnishes the necessary e.m.f. to circulate the full-load current through

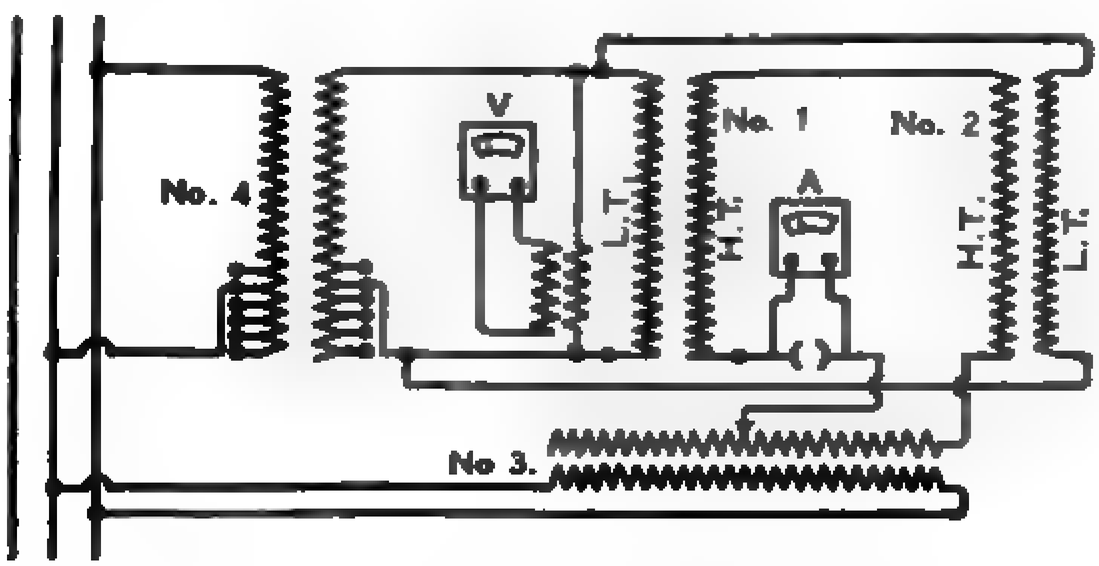


FIG. 729.—"Loading-back" test for identical transformers, load current being applied to high-tension winding.

the low-tension windings of both transformers. As these windings are inductively coupled with the high-tension windings they, too, will carry full-load current. The actual energy required for the copper losses will be supplied by the third transformer, while the magnetizing currents and core losses are supplied from the main source through transformer No. 4 on which the two transformers under test are directly connected.

Fig. 729 shows a similar loading-back arrangement, the only difference being that the application of the load current is made to the high-tension windings directly instead of to the low-tension winding.

Regulation Test

The regulation of a transformer is expressed as the per cent rise in potential from full load to no load. Thus in Fig. 730

let a transformer be loaded to its full capacity and the reading of the voltmeter V_2 be observed. Then let the load be disconnected and, with the same primary voltage applied as before, observe the secondary voltage. Call this V_1. The regulation of the transformer will now be:

$$\frac{V_1 - V_2}{V_2} \times 100 = \% \text{ regulation.}$$

Thus, if the transformer delivered 108 volts at full load and 110 volts at no load, the regulation would be:

$$\frac{110 - 108}{108} \times 100 = 1.85\%.$$

As the difference between the no-load and full-load voltage of commercial transformers is usually but a small percentage of the full-load voltage, it is very difficult to determine the regulation of a transformer by actual test. The test also involves a

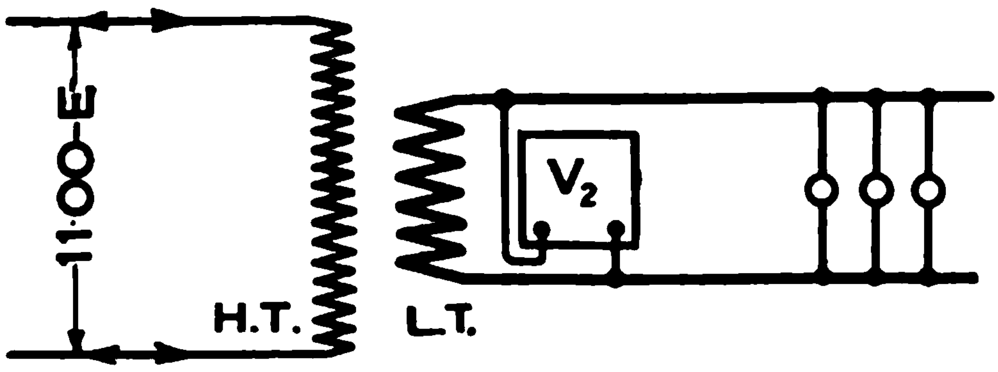


FIG. 730.—Regulation test.

considerable expense in the way of power. For these reasons, it is the custom to calculate the regulation of transformers mathematically from a knowledge of the reactance and resistance of the windings. One method is as follows:

$$E_l = \sqrt{E_n^2 - IX^2} - IR.$$

Where:

E_l = voltage at secondary terminals at full load.
E_n = voltage at secondary terminals at no load.
I = full load amperes.
X = combined reactance of primary and secondary windings in terms of the low-tension winding.
R = combined resistance of primary and secondary winding in terms of low-tension winding.

Then:

$$\frac{E_n - E_l}{E_l} \times 100 = \% \text{ regulation for unity power factor.}$$

For lagging power factor the first formula becomes:

$$E_l = \sqrt{E_n^2 - (\cos\Phi\, IX - \sin\Phi\, IR)^2} - (\cos\Phi\, IR + \sin\Phi\, IX)$$

where $\cos\Phi$ equals the power factor.

These methods of calculation give quite accurate results.

If PV_1 equals the e.m.f. applied to the primary no load, and SV_1 equals the e.m.f. of the secondary at no load, and PV_2 equals the e.m.f. applied to the primary at full load and SV_2 equals the e.m.f. of the secondary at full load, then the

$$\text{No load ratio} = \frac{PV_1}{SV_1}.$$

$$\text{Full load ratio} = \frac{PV_2}{SV_2}.$$

Efficiency

The efficiency of a transformer in terms of output may be stated as follows:

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{iron loss} + \text{copper loss}}.$$

$$\text{Efficiency} = \frac{\text{P. output}}{\text{P. intake}}.$$

Transformer Booster

Because the secondary e.m.f. of a transformer is almost exactly opposite in phase to the e.m.f. applied to the primary, the secondary winding may be connected in series with the source which supplies the primary winding of a transformer for the

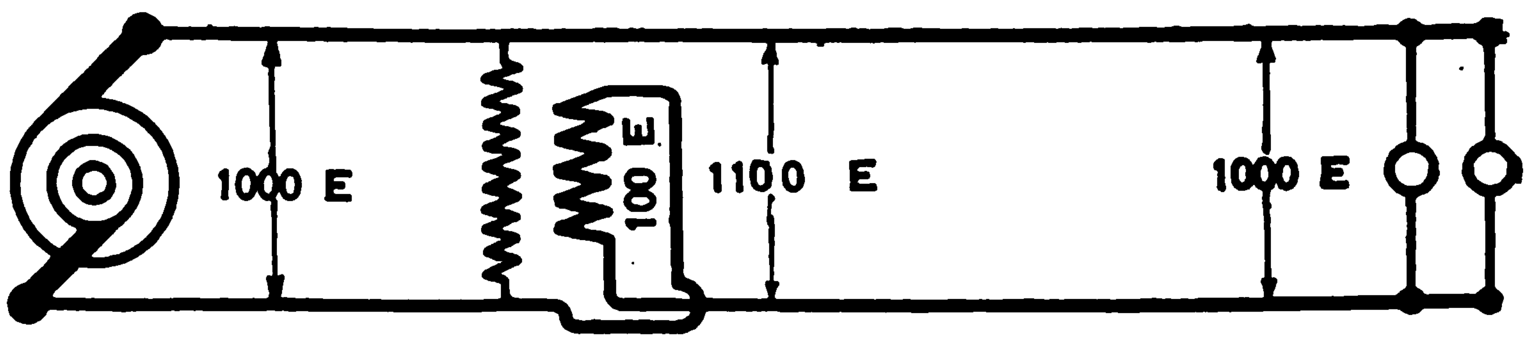


FIG. 731.—Transformer booster connections.

purpose of boosting the voltage on any circuit desired. This is illustrated in Fig. 731. Here the high-tension winding of a transformer is connected directly across an alternator. The low-tension winding of any desired voltage is connected in series with the load. If the secondary delivers 100 volts, the e.m.f. of the primary mains 1,000 volts and low-tension together will

deliver 1,100 volts, of which 100 may be lost in the feeder, and the load thus receives the same pressure which the alternator originally generated, or 1,000 volts. The transformer here resembles a shunt type of D. C. booster, for the boosting does not vary with the load but is of fixed value, at all times depending upon the voltage of the secondary. It should be remembered that, with this booster connection, the low-tension winding is subjected to a high potential and may or may not be sufficiently well insulated to withstand such voltage.

SECTION XV CHAPTER V

TRANSFORMERS

TRANSFORMER TESTING

1. Explain the method of performing the "double voltage" or "over-potential" test on a transformer. Sketch connections.
2. Explain the "insulation" or "breakdown" test for transformers. Sketch connections.
3. Explain the "heat" or "temperature" test. What percentage of load should be carried and how long should the test be run? What rise in temperature is permitted? Sketch. How much energy is required for performing this test?
4. Explain the "iron loss" test on a transformer. Sketch connections.
5. Explain the test for "exciting current" in a transformer. Sketch connections.
6. Explain the "copper loss" test on a transformer by the D. C. method. Sketch connections. What precautions should be taken to avoid the inductive kick, when the circuit is broken, from injuring the instruments?
7. Explain the "copper loss" test on a transformer by the A. C. method. Sketch connections. Is this test accurate? What corrections, if any, should be made?
8. Explain the "regulation" test for a transformer. Give formula. Sketch connections.
9. Give formula for the efficiency of a transformer. Tabulate the various losses.
10. Explain the transformer booster. Sketch connections. Is the boosting in proportion to the load, or is it fixed?

TRANSFORMERS

TRANSFORMING POLYPHASE POWER

To transform single-phase power requires the use of but one single-phase transformer.

To transform two-phase power requires the use of two transformers. Fig. 732 shows the diagrammatical arrangement of the high-tension and low-tension windings and the respective connections to the primary and secondary mains. The actual appearance of the connections on the outside of the transformer is shown in Fig. 733. Either the high or low-tension sides or

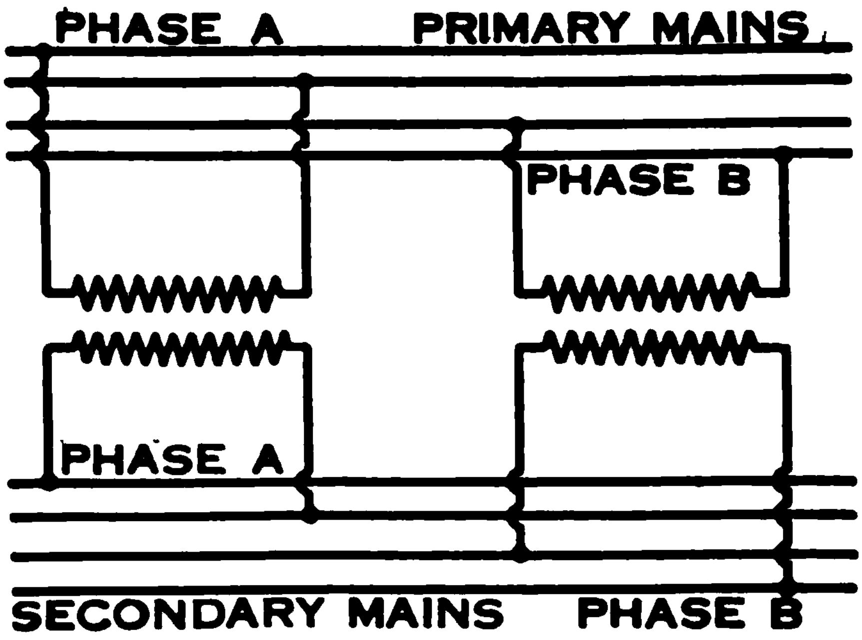


FIG. 732.—Two-phase transformation by means of two single-phase transformers.

both may be connected four-wire or three-wire as desired. The power which may be transformed is equal to the sum of the single-phase ratings of the two transformers, which are assumed to be of identical capacity.

To transform three-phase power any one of three plans may be adopted:

First: Three single-phase transformers connected in Y or in Δ. Fig. 734 shows the theoretical arrangement of the high-tension and low-tension windings of three single-phase transformers connected in Y. Here the high-tension leads *A-B-C* supply the primaries, while the low-tension windings feed the three mains *D-E-F*. The outside appearance of the transformers when

so connected is shown in Fig. 735. Corresponding ends from each of the three transformers are taken out on the right of the transformer cases and connect to the middle point of the Y at *G*. The remaining ends of the high-tension windings connect to the lines *A*, *B* and *C*. The low-tension terminals project from the

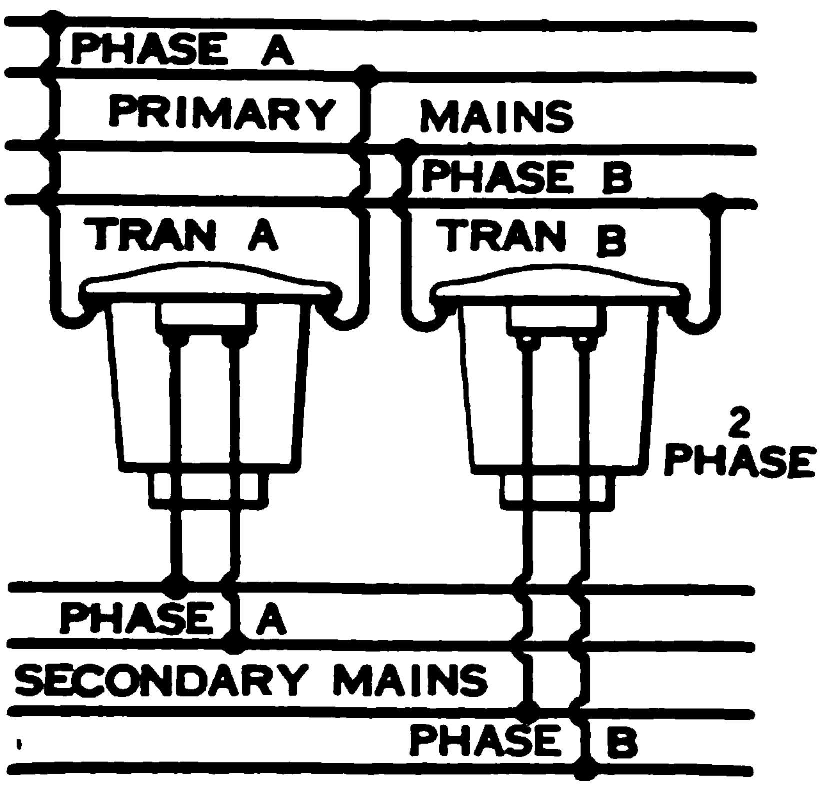


FIG. 733.—Outside appearance of connections of two single-phase transformers employed for two-phase transformation.

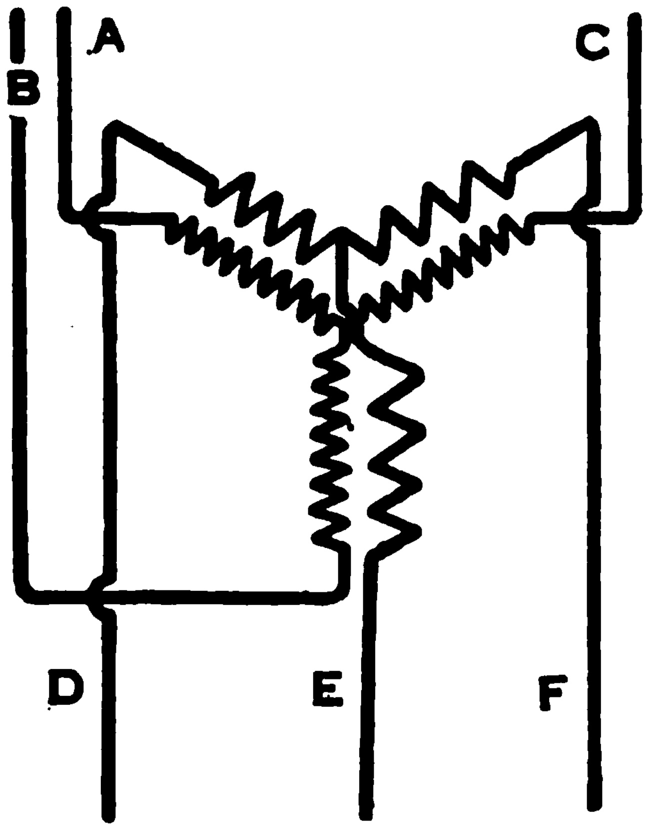


FIG. 734.—Theoretical connections between high-tension and low-tension winding of three transformers connected in Y.

front of the case, the right or corresponding ends connect to the middle point of the Y at *H*, while the remaining terminals *D*, *E* and *F* lead to the secondary circuit.

A Δ-connected bank of three transformers is diagrammatically

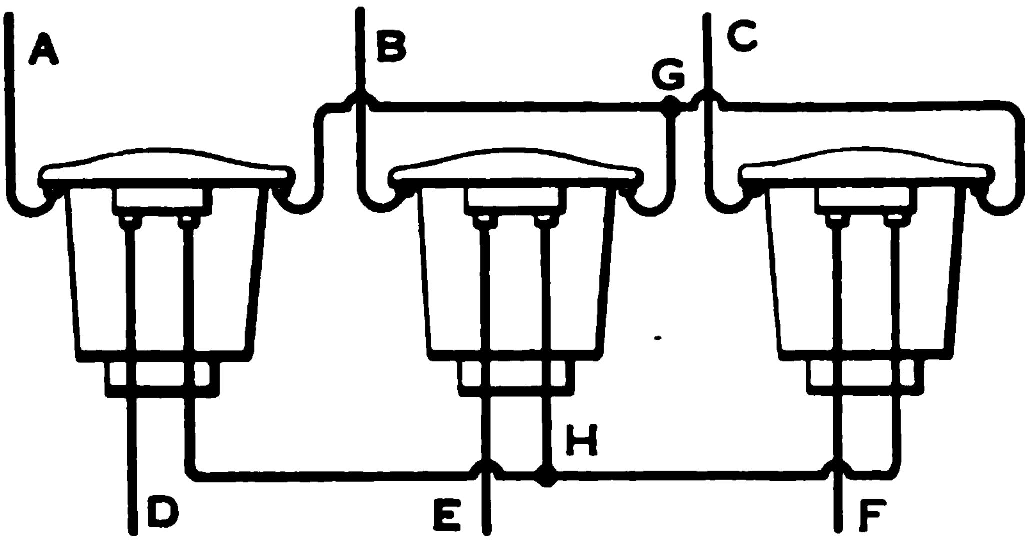


FIG. 735.—Actual connections between high-tension and low-tension winding of three transformers connected in Y.

illustrated in Fig. 736. Here, the terminals of the high-tension side of the Δ lead to the primary mains *A*, *B* and *C*. The

terminals of the low-tension side lead to the secondary mains *D*, *E* and *F*. The actual appearance of the outside of the cases of a Δ-connected bank is shown in Fig. 737. Here the three high-tension windings are connected as shown in a closed circuit or mesh. Taps from between each of the two transformers lead to the high-tension mains *A*, *B* and *C*. The low-tension connections project from the front of the cases and are also connected in closed mesh. Taps from between each two transformers lead to the secondary mains *D*, *E* and *F*.

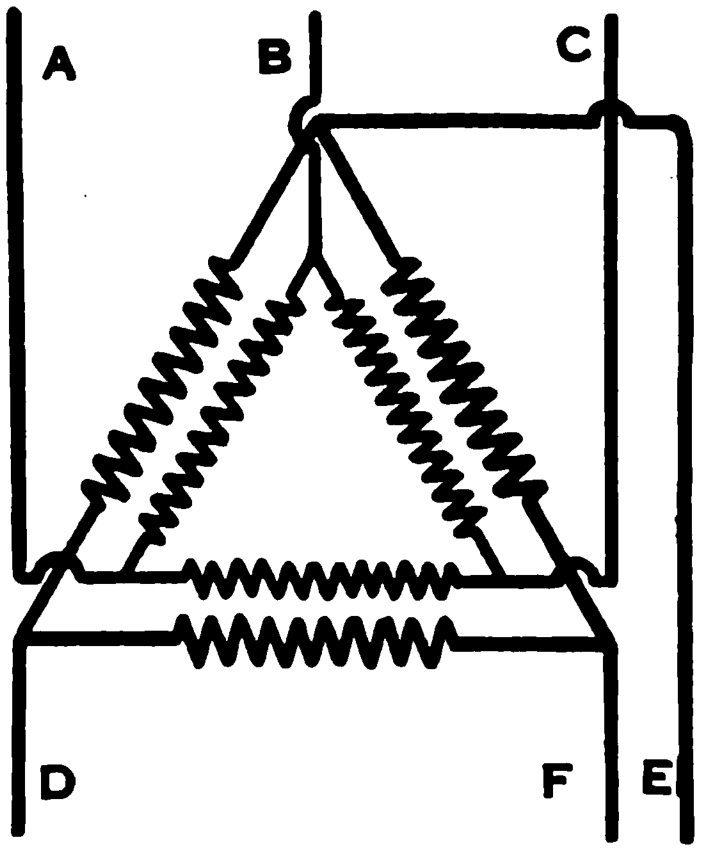


FIG. 736.—Theoretical connections between high-tension and low-tension winding of three transformers connected in Δ.

Second: Three-phase power may be transformed by the use of two single-phase transformers connected in either T or V. If 30 kilowatts of power is to be transformed, three 10-kilowatt single-phase transformers may be employed. If, however, two 17.3-kilowatt transformers are

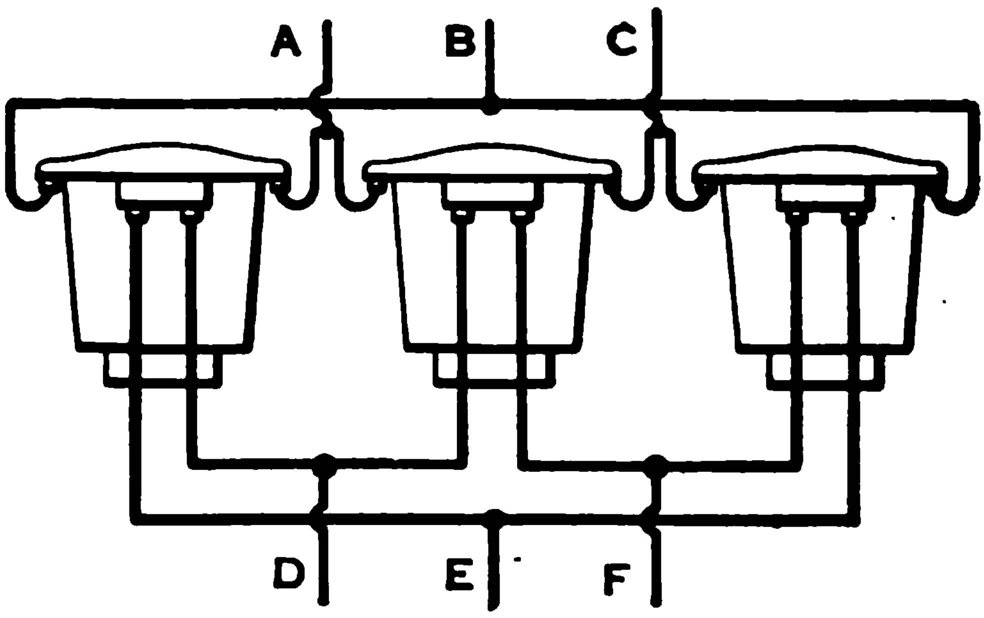


FIG. 737.—Actual connections between high-tension and low-tension winding of three transformers connected in Δ.

available, the same 30 kilowatts can be transformed just as readily by the T or V connection. (See page 62.)

The T connection is illustrated in Fig. 738. Here, one end of one winding of the transformer *A* is connected to the middle

point of one winding of the transformer B. The connections are duplicated on the other windings. The relations which these windings bear to each other are illustrated in Fig. 739. If the winding A-B is adapted for 100 volts, then one-half of that winding, or A-D, is designed for 50 volts. If at the point D, a winding D-C, designed for 86.7 volts, is connected, it will be observed that $A\text{-}C = \sqrt{AD^2 + DC^2} = \sqrt{50^2 + 86.7^2} = 100$. Thus, if a force of 100 volts is applied to A-C, it may be resolved into two forces, one of 50 volts in the direction A-D and the other of 86.7 volts in the direction D-C. Likewise, if a force of 100 volts is applied between C and B, it may be considered as

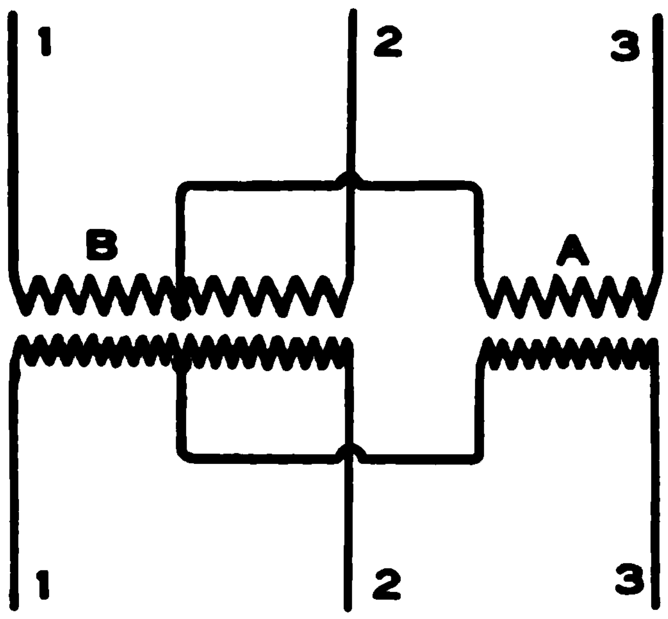


FIG. 738.—Theoretical arrangement of circuits in T connections between two transformers.

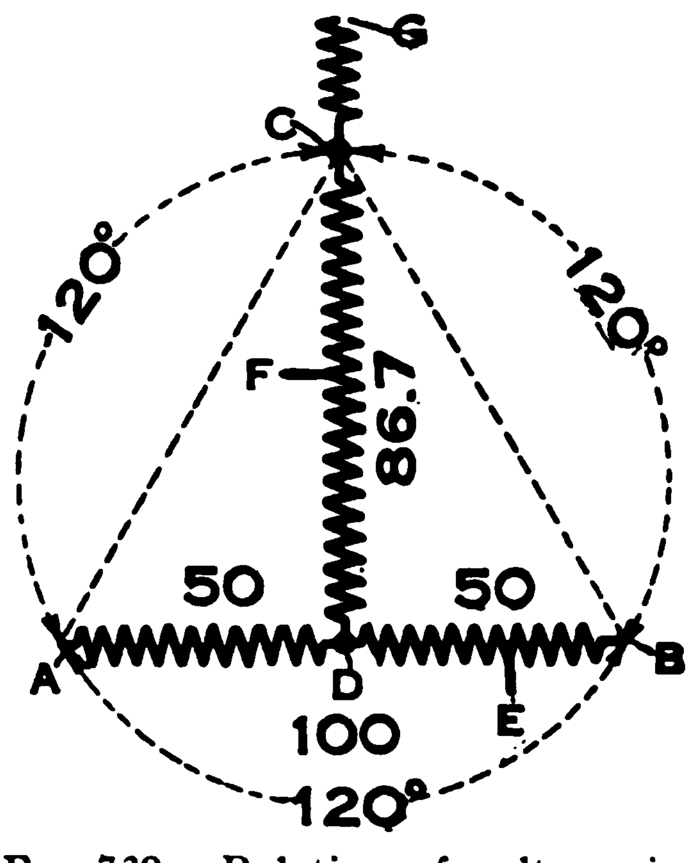


FIG. 739.—Relation of voltages in T-connected transformers.

resolved into two forces, one 86.7 volts in the direction C-D and the other 50 volts in the direction D-B. Finally, if a force of 100 volts be applied to A-B, these three forces in the two transformers may be so combined as to give symmetrical three-phase currents, although there are but two iron cores instead of three.

In order to transform three-phase power it is necessary that there be at least two magnetic paths in which the fluxes may differ by some phase angle. Polyphase power cannot be transformed by a single transformer having a single magnetic circuit, for, if polyphase currents were applied to two or more windings on such a core, their separate magneto-motive-forces would simply produce one resultant flux and the induction on the low-tension winding would be of but a single e.m.f. and

current. The outside connections to the transformer cases for two transformers connected in T is shown in Fig. 740.

Another possible arrangement for three-phase operation with two transformers is shown in Fig. 740. This is called the **resultant mesh, open Δ or V** connection. It is the same as the Δ connection shown in Fig. 736 but with one transformer omitted. Thus two 17.3-kilowatt transformers in Fig. 741 would replace three 10-kilowatt transformers in Fig. 736. Obviously, if a voltage is impressed on *A-C*, 60° out of phase with each of two other voltages impressed upon *A-B* and *B-C* respectively, it would produce a current in *A-B-C* which is out of phase with the currents in each of the transformer primaries. The phase *A-B* would induce a secondary e.m.f. in *D-E*, the phase *B-C* would likewise transform to the winding *E-F*, while the third phase, for which no winding is provided, impressed across *A-C*, would induce a third voltage in *D-F* in phase therewith through the medium of the two transformer windings in series.

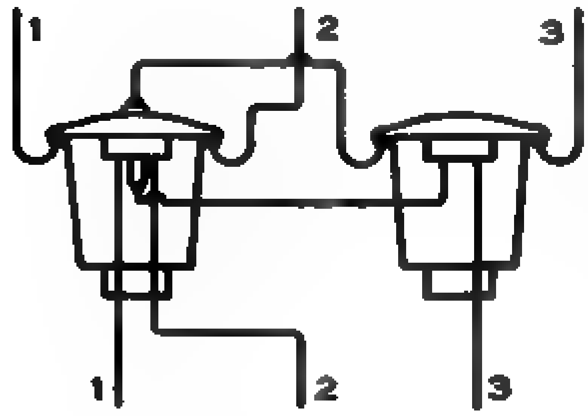


Fig. 740.—Actual appearance of connections of two transformers connected in T.

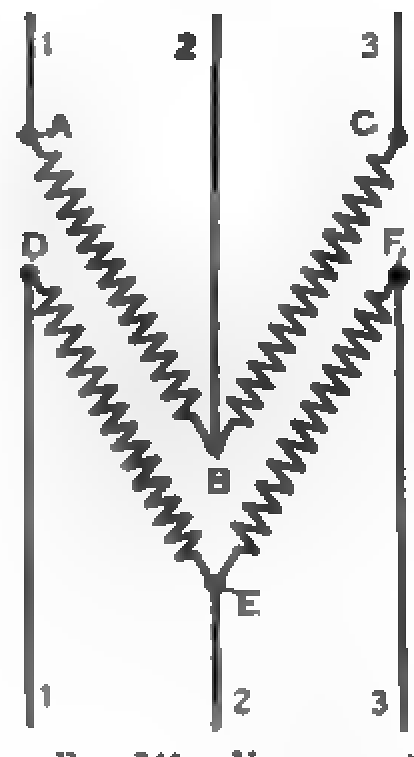


Fig. 741.—V or open-Δ connections of two transformers for three-phase circuit.

If one phase of a Y-connected bank of transformers, Fig. 734, burned out on either the high-tension or low-tension side, the remaining two phases thrown in series would merge their voltages, currents and fluxes into a single-phase resultant. The ability to operate three phase would then be lost and the system would be reduced to single-phase operation.

If however a closed Δ connection, Fig. 736, was being used, the burning out of either high tension or low tension of one side would simply alter the connections to an open Δ as in Fig. 741. Th

system would continue to operate as a polyphase system with a capacity of 58% of the original bank. The Δ connection therefore assures more reliability in operation than the Y connection.

In transformers designed for either T or V connections there must be provided 15% greater copper than that normally required for a given single-phase rating. The reason for this is that the current in and line voltage across the transformer differ from each other by 30° at 100% power factor. Thus for the V connection, Fig. 742, the current in the line *A* has the direction *O-C*, while the voltage has the direction *G-H*. It is evident that these two values are also displaced in phase by 30° for the

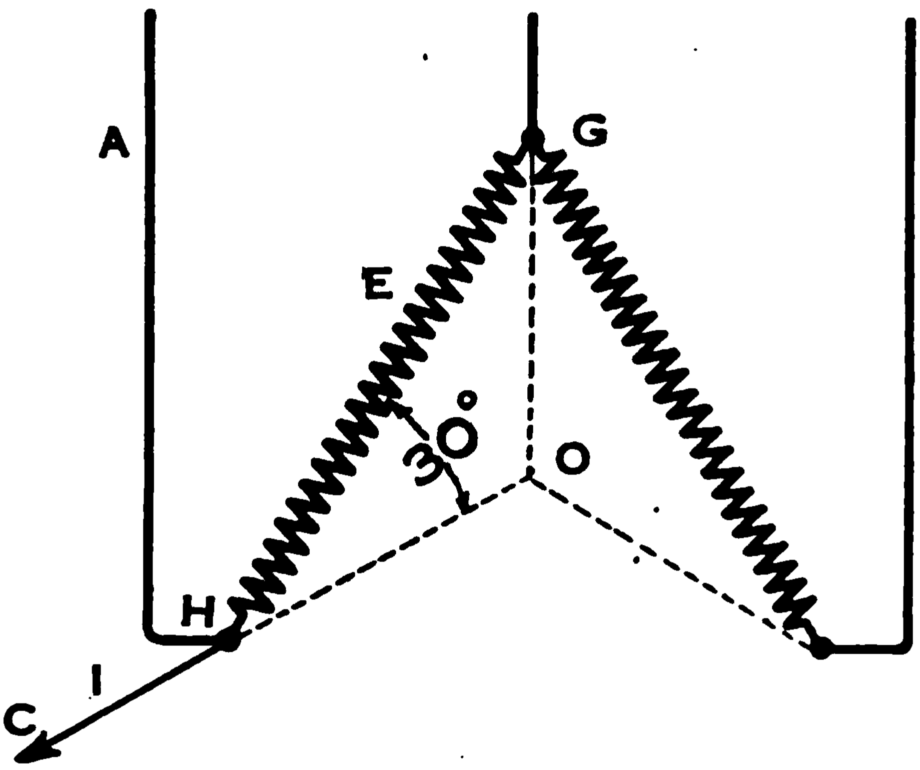


FIG. 742.—Phase relation of line-currents and voltages to phase currents and voltages in V or open-Δ connection.

T connection, Fig. 743, for the current in the line *A* has the direction *O-C*, while the voltage has the direction *G-H*.

To deliver a given power at unity power factor, $P = E \times I \times \sqrt{3}$, but when the current and voltage differ in the transformer winding by 30°, the expression for the power will be $P = E \times I \times \sqrt{3} \times \cos 30°$ ($\cos 30° = 0.866$). Now to transform a given power with a T or V connection either the voltage or current must be increased. As the voltage is fixed, the current must be increased. Thus if a current of 10 amperes were required at 100% power factor, then the increase in current due to this phase angle will be

$$\frac{10}{0.866} = 11.5 \text{ amperes}$$

which is 15% greater than 10 amperes. Transformers having T or V connections are provided with this 15% excess of capacity

in copper. Thus to transform 30 kilowatts as in the example on page 60, would require three 10-kilowatt transformers. But if two transformers are used with V or T connection, 15% additional capacity will be required. 15% of 30 kilowatts equals 4.5 kilowatts, making a total of 34.5 kilowatts. This divided in two gives 17.3 kilowatts for each transformer.

Sometimes two core-type transformers for operation in T or V are placed one on top of the other and then mounted in a single case. This economizes floor space. Such an arrangement is called a duplex transformer.

Third: Three-phase power may be transformed by means of a single composite transformer with three magnetic paths through which there may circulate three fluxes differing in their phase relation. These fluxes, however, need not be confined entirely

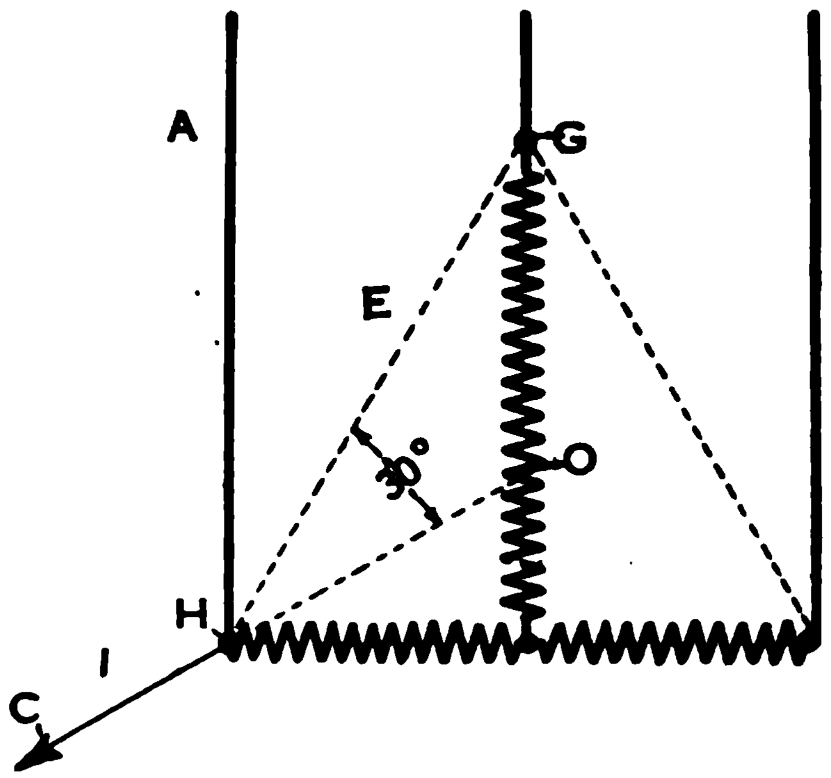


FIG. 743.—Phase relation of line-currents and voltages, to phase currents and voltages, in T connection.

to separate and independent cores. Certain portions of the iron may carry the fluxes of two or all three phases:

The resultant of two or three fluxes, out of phase with respect to each other, is less than their arithmetical sum, hence there will be an economy in iron in the construction of a composite transformer over that to be found in three single-phase units.

Theoretically the cores of a polyphase transformer should be arranged in the form of a triangle with a magnetic yoke connecting the three cores on the top and another on the bottom, giving in effect a Δ arrangement of the fluxes. Practically it has been found that these three cores may be placed in line, giving a better and cheaper mechanical construction.

The plan of the core-type composite transformer is shown in Fig. 744. Here the high-tension windings *A*, *B* and *C* are wound one upon each leg, the low-tension winding, *D*, *E* and *F*, being interlaced therewith. The fluxes, being 60° apart in phase, will always find a satisfactory circuit through the iron so provided, for the flux in the core *C-F*, for instance, will be the geometric sum of the fluxes in the core *A-D* and the core *B-E* at that particular instant.

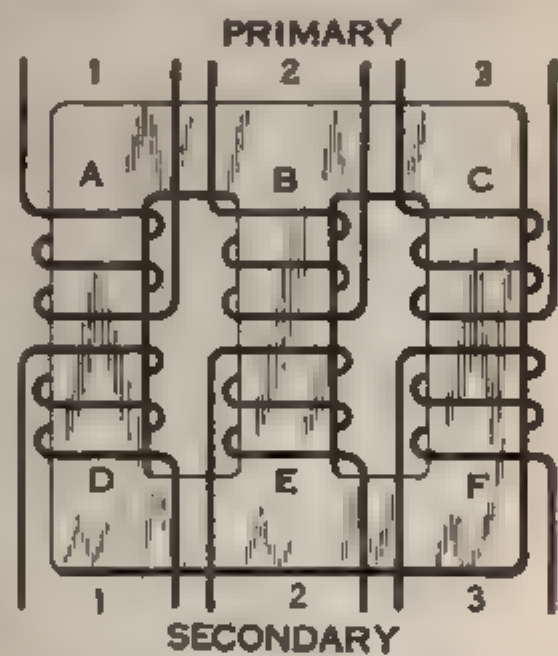


FIG. 744.—Theoretical arrangement of high-tension and low-tension circuits on three-phase composite transformer.

The core-type transformer here shown in Fig. 744 becomes inoperative if one of the phases is short-circuited because the flux from the other two phases being driven through the short-circuited winding causes the production of excessive current therein. If, however, one phase is open circuited, the remaining two may operate satisfactorily if reconnected in T or V. Fig. 745 illustrates the actual construction of a General Electric three-phase core-type transformer.

The relation between the sizes of single-phase transformers and a core-type composite transformer is shown in Fig. 746. Here the leg *A-D* represents one core having a high-tension and low-tension winding capable of handling 1 kilowatt. *B-E* also has a capacity of 1 kilowatt. As it stands it is a 2-kilowatt single-phase transformer. If, now, a third leg of iron *C-F* be added, equal in cross-section to *B-E*, and if a winding of one kilowatt be placed thereon, the transformer becomes a composite 3-kilowatt transformer having a capacity of 1 kilowatt per leg.

The relative cost of transformers for transforming three-phase power by the three methods may now be compared.

By the first method the cost is three times the cost of one 1-kilowatt transformer.

By the second method the cost is two times the cost of one 1.73-kilowatt transformer.

By the third method the cost is 1.73 times the cost of one 2-kilowatt transformer.

The third method is the most economical one for transforming three-phase power, but no three-phase composite transformer is as efficient as a single-phase transformer of the same total output and design. That is to say, if 300 kilowatts are to be

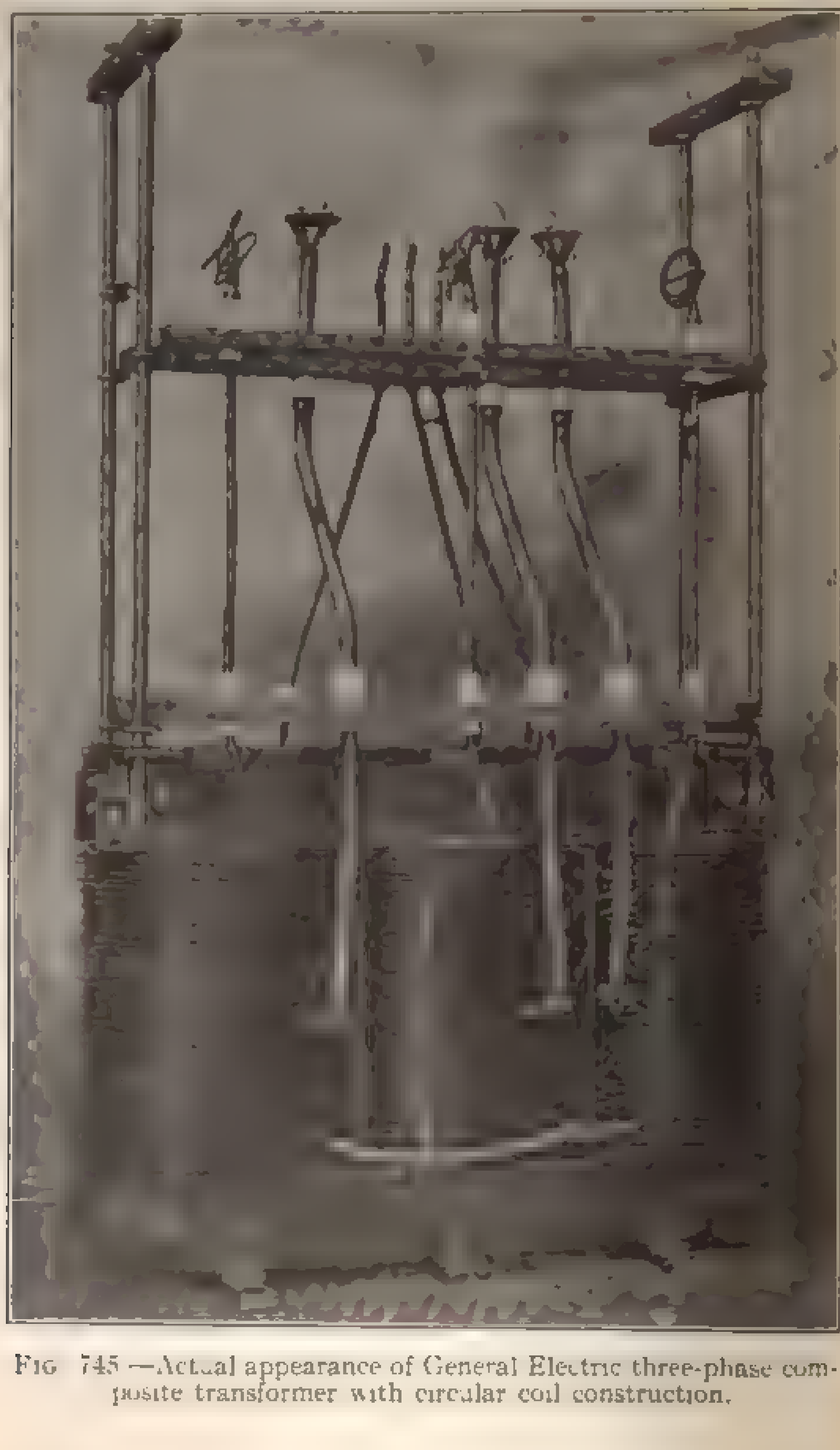


FIG. 745.—Actual appearance of General Electric three-phase composite transformer with circular coil construction.

transformed, the efficiency of one 300-kilowatt composite transformer would be higher than that of three 100-kilowatt single-phase transformers employed to do the same work, but a 300-kilowatt single-phase transformer is more efficient than a 300-kilowatt composite three-phase transformer. Many large capacity high-voltage composite transformers are of the shell type. The construction is illustrated in Fig. 747. The high-tension and low-tension windings of the three phases are wound upon the central section of the core laminations *A*, *B* and *C*. The magnetic circuit being divided, the path through *D* will be one-half the cross-section of the path through *A*. As the mag-

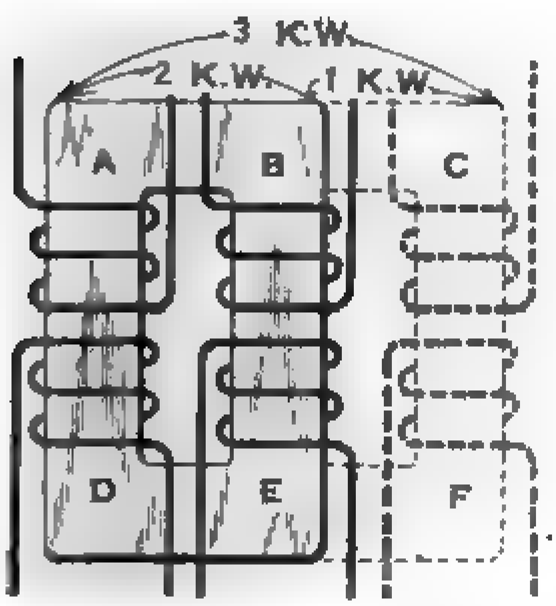


Fig. 746.—Showing relative amounts of iron and copper required in three-phase composite transformer compared with a single-phase transformer.

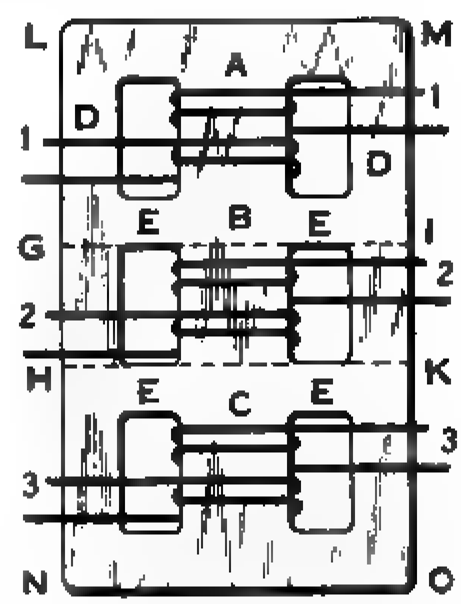


Fig. 747.—Theoretical arrangement of iron and copper in three-phase shell-type transformer.

netic fluxes in *A*, *B* and *C* are out of phase with each other the cross-section of the paths *E* need be no greater than the cross-section of the paths *D*. For a given capacity in phase 1, a single transformer would have the dimensions outlined by *L-M*, *G-I*. Phase 3, if operated alone, would require a transformer of the dimensions *H-K-N-O*. Because of the difference in phase of the fluxes it will be observed that the iron for phase 2 is less than the amount required for phase 1 and phase 3 by the keeper sections *E-E-E-E*. The actual saving in iron effected by this arrangement is between 10 and 20% of the amount which would be required for three single-phase transformers handling

the same amount of power. The plan of the three-phase shell-type transformer shown effects some economy in floor space.

Scott Connection for Transformers

For changing from two phase to three phase a special arrangement of the transformers called the **"Scott Connection"** is em-

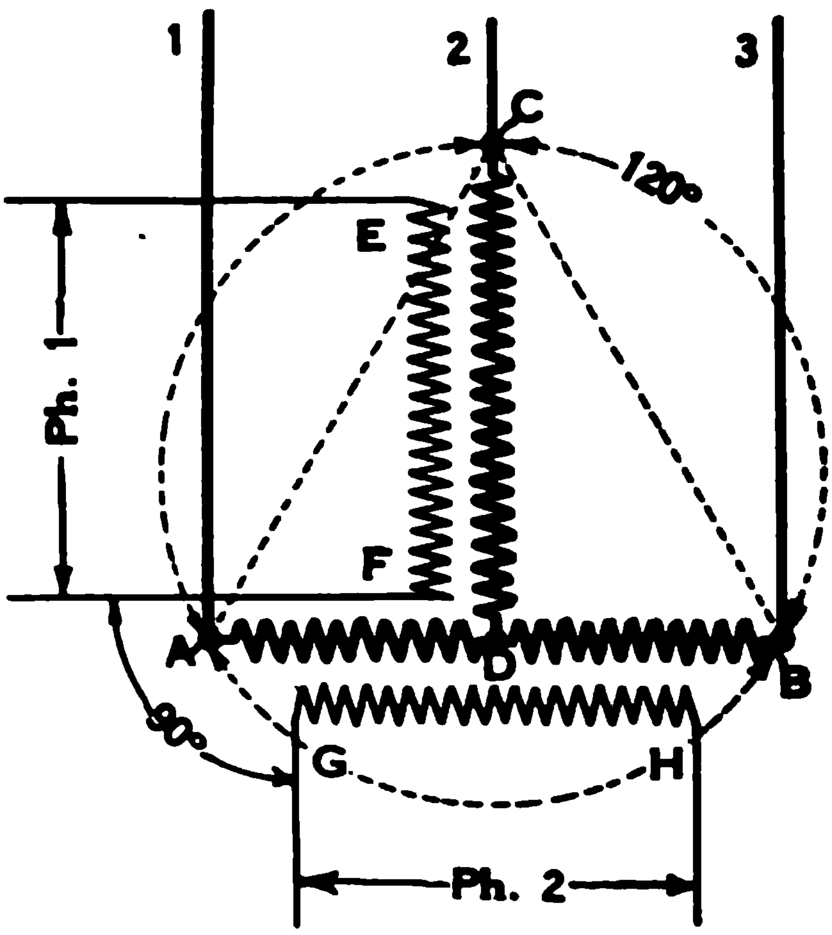


FIG. 748.—Theoretical arrangement of high-tension and low-tension circuits of two "Scott-connected" transformers.

ployed, Fig. 748. The high-tension windings of two transformers are connected to a two-phase source, in which the e.m.fs. are displaced from each other by 90°. One end of the low-tension winding of phase 1 is connected to the middle point of the low-tension winding of phase 2. The remaining three low-tension terminals supply the three-phase secondary system. As already explained in connection with Fig. 739, two forces 90° apart in phase may be resolved into components which will deliver three forces 120° apart in phase. Let A-B equal 100 volts,

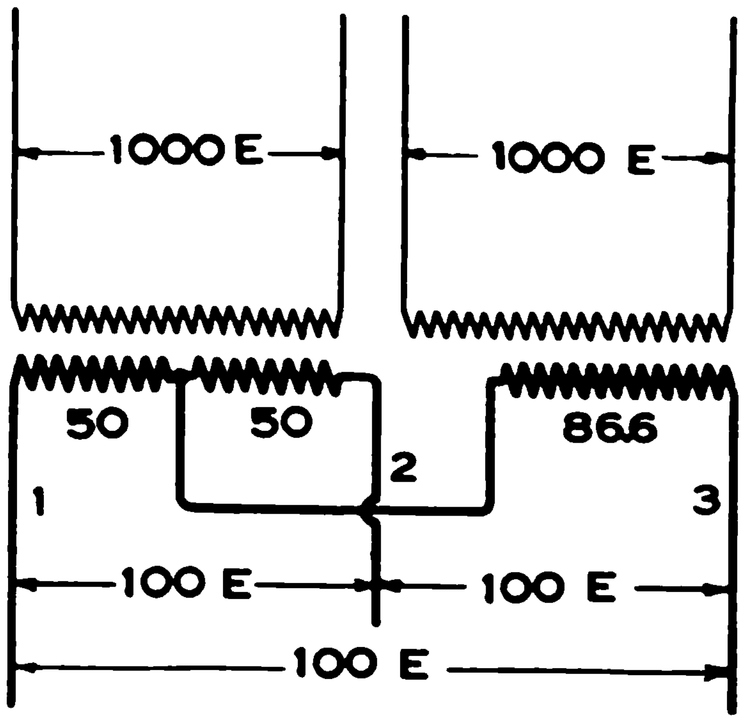


FIG. 749.—Relation between voltages in "Scott-connected" transformers.

C-D, 86.7 volts and *A-D* and *D-B* each 50 volts. If now a 1,000-volt source is connected to the high-tension sides of the two transformers, as in Fig. 749, there will be induced, in the two low-tension windings, 100 volts and 86.7 volts respectively. The combination of each half of the 100-volt winding and the 86.7-volt winding will give three symmetrical e.m.fs. of 100 volts each on the low-tension side. The outside appearance of two transformers Scott connected is shown in Fig. 750.

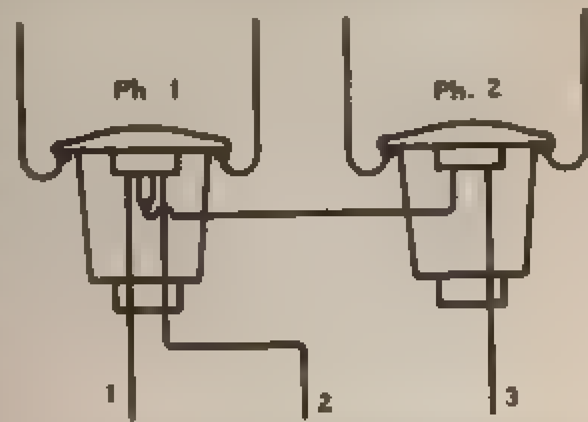


Fig. 750.—Actual external appearance of two "Scott-connected" transformers.

Three-Wire Transformers

Where transformers are to be operated on the three-wire single-phase system it is not necessary to use two transformers of 110 volts each in series to supply the two sides of the system.

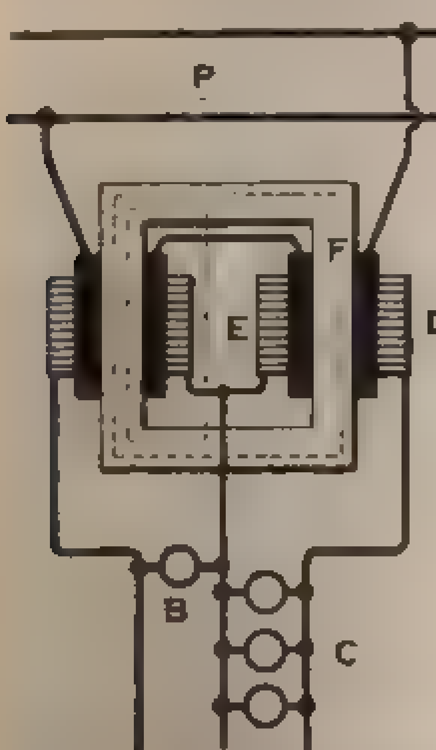


Fig 751.—Ordinary core-type transformer not adapted for three-wire operation.

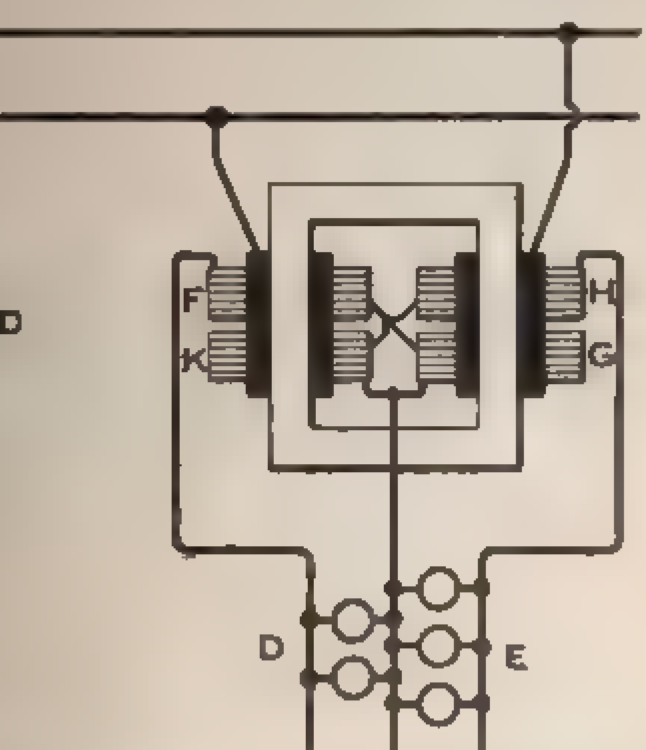


Fig 752.—Core-type transformer especially designed for three-wire operation.

A single transformer of the shell type or cruciform type may be employed with a tap taken from the middle point of the winding for the neutral wire. If a core-type transformer is em-

ployed, trouble in regulation will be experienced unless a special design is used. Suppose, for example, that a core-type transformer has its high tension winding in two parts connected in series across the primary mains *P*, Fig. 751, while the low-tension winding, also divided in two parts, is connected in series and a tap from the middle point used to supply the neutral of a three-wire system. If now the system becomes heavily overloaded with an excess of lamps at *C*, the current drawn through the secondary section *D* will react on the magnetic flux, diverting it from the core through the path *E*. The flux through *F* being thereby reduced, the voltage on the lamps *C* falls below that on the lamps *B*. The greater the difference in load the greater the difference in voltage.

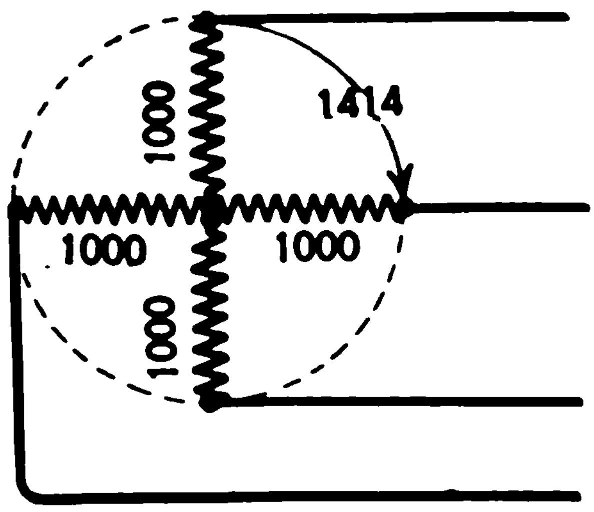


FIG. 753.—Various voltages available from two-phase alternator when the two phases are tied together at the middle.

If, however, the transformer secondaries are divided into sections as in Fig. 752, and the section *F* is cross-connected in series with the section *G* to supply the lamps at *D* while the section *H* is cross-connected with the section *K* to supply the lamps at *E*, then in case of an overload on one side of the system, such as *E*, the excess of current demanded is derived equally from *H* and *K* and therefore reacts equally on the total magnetic flux. There is therefore no perceptible inequality of voltages accompanying unbalanced loads. With large transformers the sections are still further subdivided and interconnected so as to minimize leakage.

The various arrangements of single-phase transformers for a two-phase system are shown in Fig. 754. The two windings of the alternator supplying the system are connected together at a middle point, Fig. 753, which accounts for the various voltages obtained. Single-phase transformation with one transformer is shown at *A*, Fig. 754; two-phase four-wire transformation with two transformers at *B*; a two-phase three-wire **"T"** connection changing to two-phase four-wire at *C*; and a **"Scott"** connection changing from two-phase to three-phase at *D*.

Fig. 755 illustrates the various arrangements of single-phase transformers for three-phase operation. Thus *A* shows a Δ to Δ

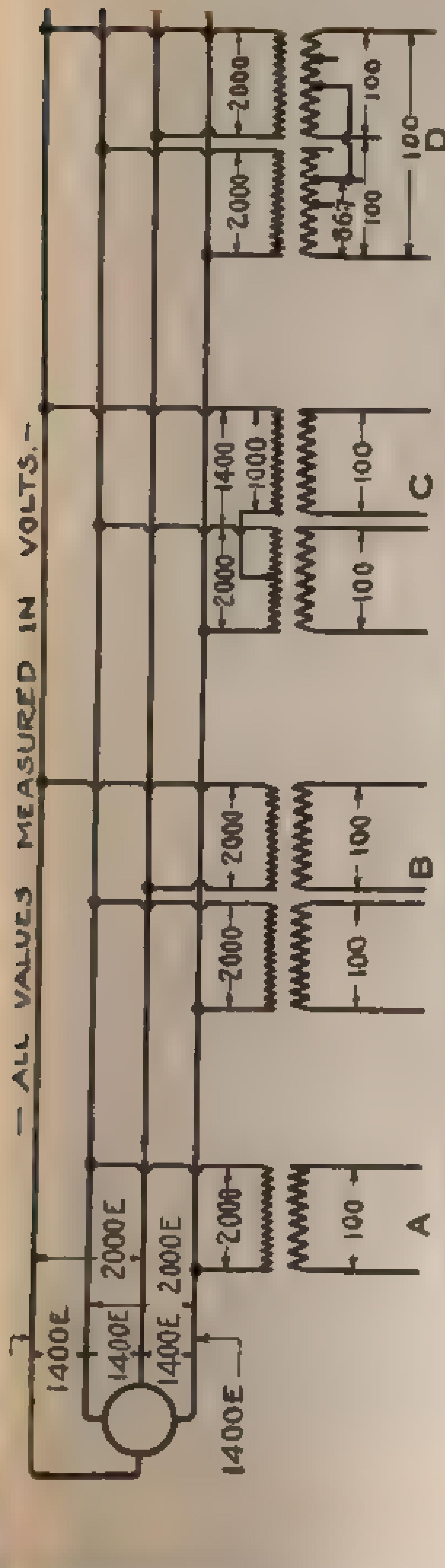


FIG. 754 Various possible arrangements of transformers on two phase, four-wire alternator.

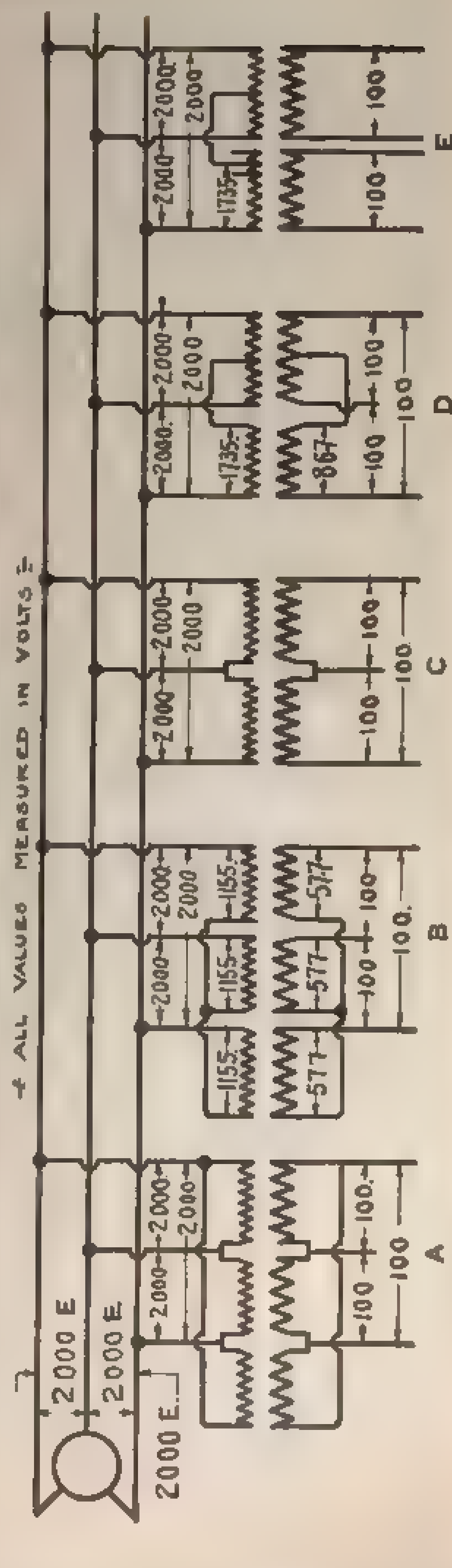


FIG. 755.—Various possible arrangements of transformers on three-phase, three-wire alternator.

connection, *B* a Y to Y connection, both employing three transformers. *C* is a **V** connection and *D* is a **T** connection, both of these employing two transformers each, while *E* is a **"Scott"** connection, three-phase to two-phase.

Many attempts have been made to distribute a single-phase

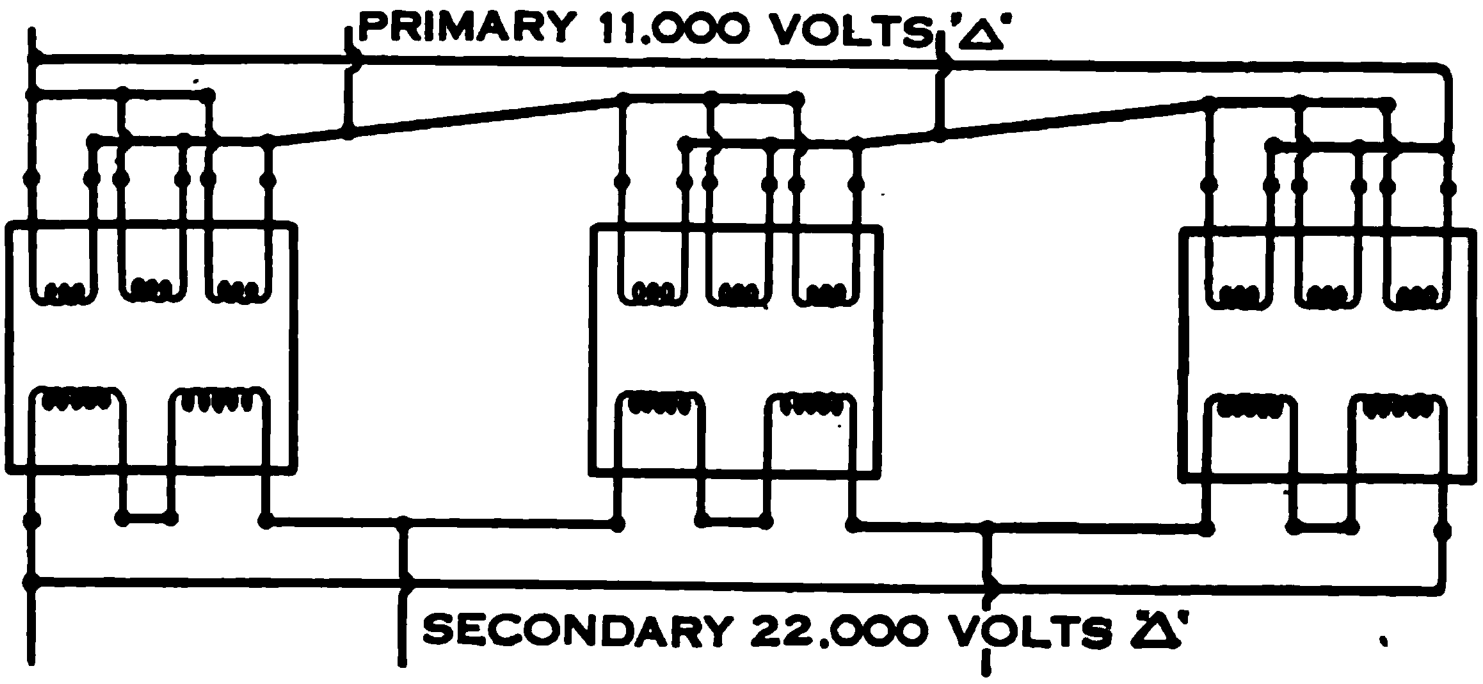


FIG. 756.

load equally between the phases of a three-phase source by some scheme of transformer connections, but this has never been satisfactorily accomplished. The best that can be done is to divide a single-phase load into two parts and connect it equally

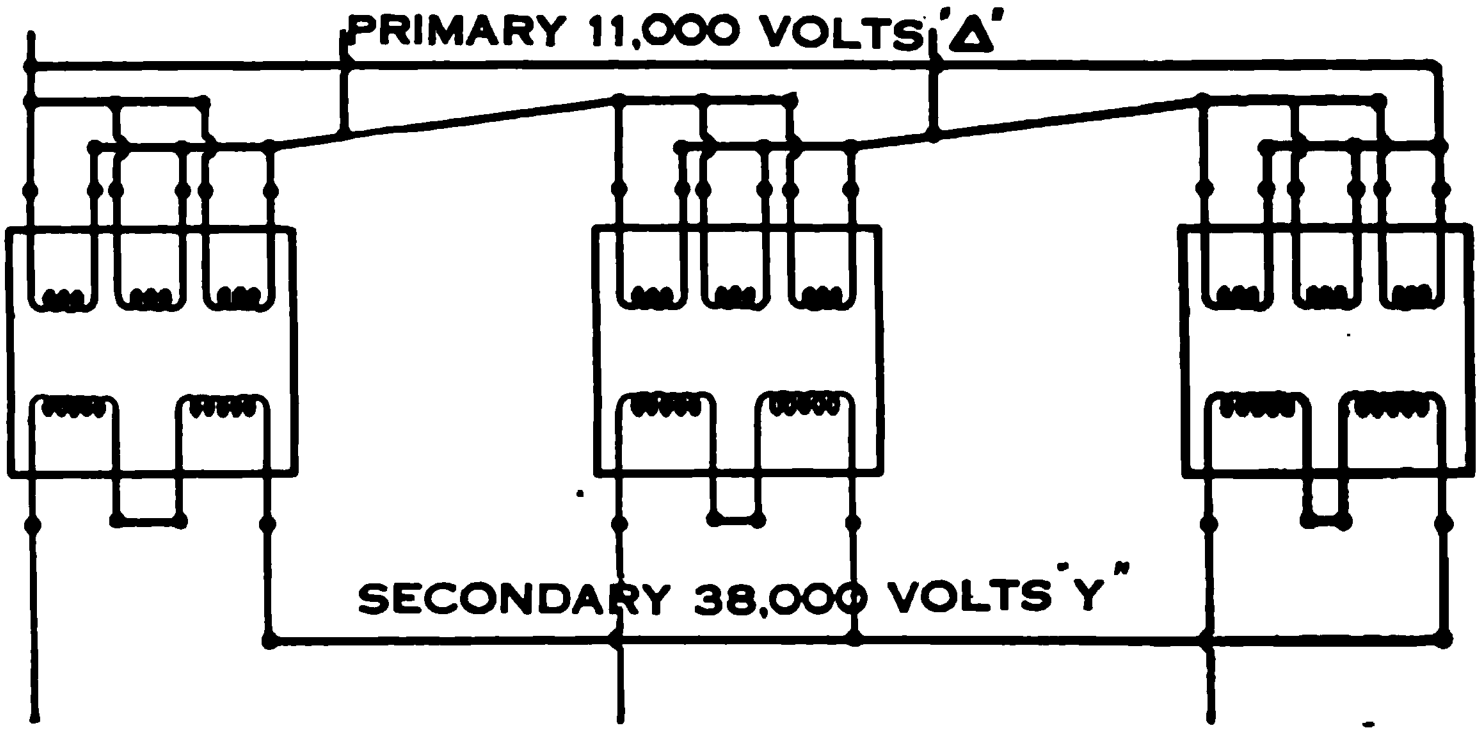


FIG. 757.

upon the two phases of a pair of Scott-connected transformers. This will divide the load equally on the three primary phases.

The flexibility of voltages obtainable through three single-phase transformers provided with three sections in or

and two sections in the other is shown first in Fig. 756. Here the three sections on one side of each transformer are connected in parallel. These three transformers are then connected in Δ. The two sections on the other side of each transformer are connected in series. The three transformers are then connected in Δ on that side. With 11,000 volts employed on the primary, 22,000 volts is delivered in the secondary.

Without altering the primary connections a change of the high-tension sides from Δ to Y, Fig. 757, will enable 38,000 volts

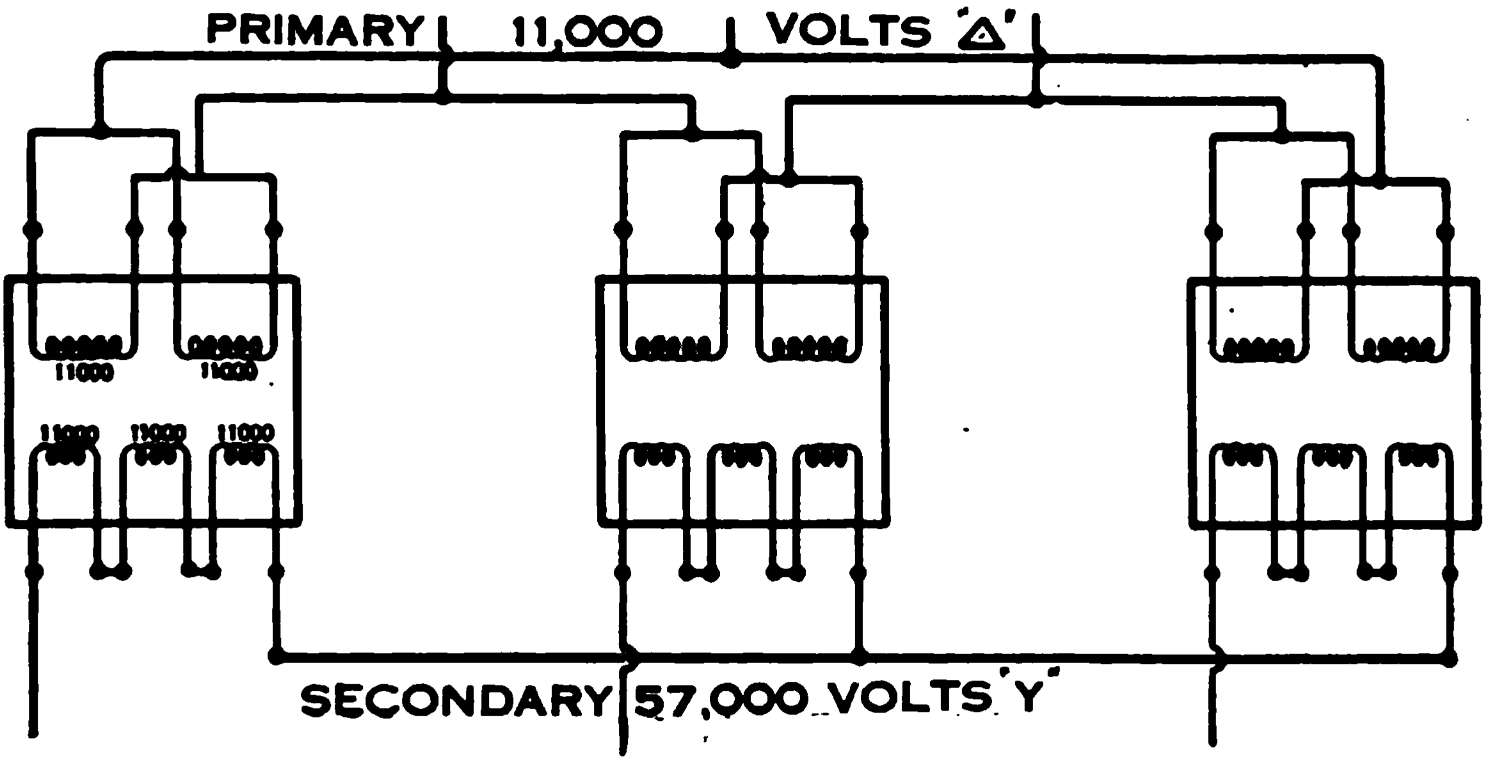


FIG. 758.

to be obtained instead of 22,000. If the transformers are now turned around and the two sections of each transformer are placed in parallel and the three transformers then connected in Δ and 11,000 volts applied, then with the three sections on the high-tension side of each transformer connected in series and the three transformers themselves connected in Y, Fig. 758, 57,000 volts may be obtained. Thus with a primary e.m.f. of 11,000 volts available, three separate secondary voltages may be obtained according to the connections employed.

SECTION XV CHAPTER VI

TRANSFORMERS

TRANSFORMING POLYPHASE POWER

1. Sketch connections showing transformers required for transforming two-phase power.
2. Sketch three single-phase transformers connected in "Y." Give diagrammatical sketch and also the actual connections as they would appear on the outside of the three transformer cases.
3. Sketch three single-phase transformers connected in "Δ." Give diagrammatical sketch and also show connections as they would appear on the outside of the three transformer cases.
4. Sketch two transformers connected in "T" for three phases. Give diagrammatical sketch and also the connections as they would appear on the outside of the transformer cases. Explain the principle involved.
5. Sketch two transformers connected in "V" or "open Δ." Give diagrammatical sketch and also connections as they would appear on the outside of the transformer cases.
6. Must the aggregate capacity of two transformers for "T" or "V" connection on a three-phase system be greater than if three single-phase transformers were used. If so, how much and why?
7. Explain the principle of the composite three-phase "core" type transformer. Sketch. What are its advantages and disadvantages? What is its relative efficiency compared with three single-phase transformers of the same aggregate capacity and with one single-phase transformer of an equal capacity.
8. Explain the principle, construction, advantages and disadvantages of the three-phase "shell" type transformer.
9. What is the advantage of the "Scott connection" for transformers? Sketch two transformers "Scott connected?" Give the relative e.m.fs., of all phases on both sides. Give diagrammatical sketch, also the connections as they would appear on the outside of transformer cases.
10. Explain what modification is necessary in the construction of an ordinary "core" type transformer to adapt it for use on a three-wire system.

TRANSFORMERS

AUTO-TRANSFORMERS

An **"Auto-transformer"** differs from the ordinary type in that it has a single continuous winding which is used for the impressed voltage and furnishes one or more secondary voltages from the same winding. In an ordinary transformer the high-tension and low-tension windings are most carefully insulated from each other, but if the voltages are so low that both are harmless, or so high that both are dangerous, or if there is a comparatively small difference in voltage between the two sides, there is no advantage in insulating the windings from each other. In the auto-transformer no attempt is made to insulate the supply circuit from the load circuit because a decided economy in material results from having these two circuits common to each other. An auto-transformer may be employed to either raise or lower the voltage as desired.

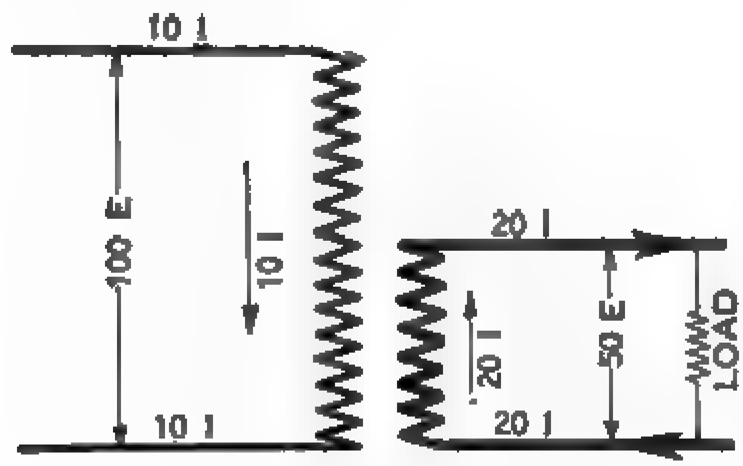


FIG. 759.—Currents, voltages and windings involved in an ordinary transformer.

Beside the fact that in ordinary transformers the windings are separate and insulated from each other while in auto-transformers they are connected, there is another fundamental difference. With ordinary transformers the power transformed is the same as the power delivered to the load. With auto-transformers the power transformed is always less than the power delivered to the load. Herein lies the economy in the use of auto-transformers. With a given voltage the size of an ordinary

transformer varies directly as the power transformed. Therefore, if it is possible to obtain a given output without transforming all the power, a net saving in the cost of the transforming apparatus will result. Consider an ordinary transformer with two windings in Fig. 759. The high tension receives 100 volts and 10 amperes. The low-tension winding delivers 50 volts and 20 amperes. By altering the arrangement to that shown in Fig. 760, one-half of the copper—namely, that required by the low-tension winding—is saved entirely. The same high-tension winding is used as before, but a tap is taken at the point *B* for the secondary load. Ten amperes drawn from the source enters the high-tension winding at *A* and flows to the point *B*. It

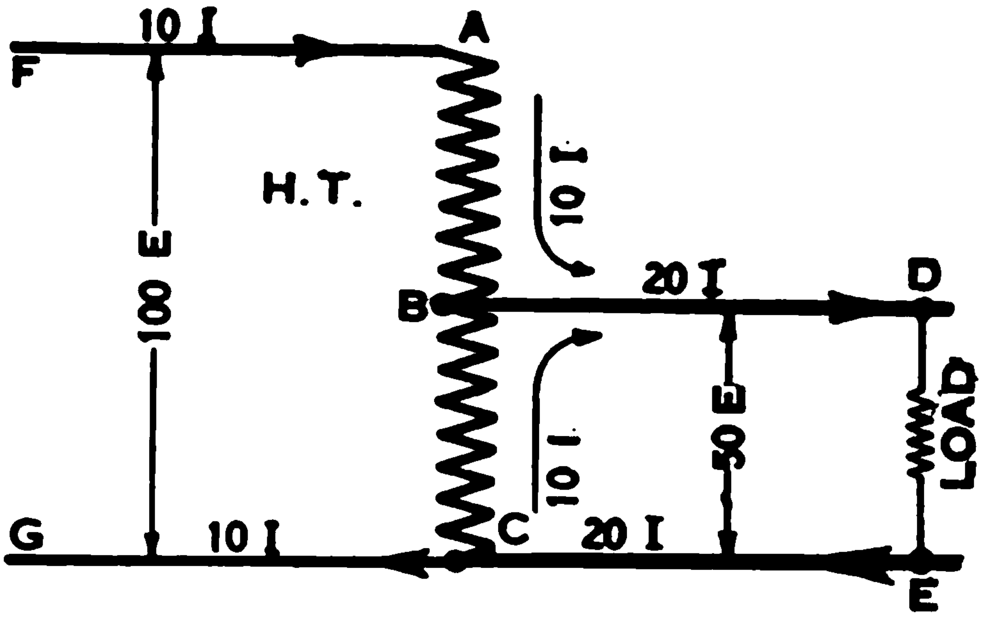


FIG. 760.—Economy of copper effected in auto-transformer.

falls in potential 50 volts to that point. In so doing 50 volts is produced in the section *B-C* (neglecting losses). Another 10 amperes at this pressure flows in the opposite direction. The 10 amperes, flowing upward through *C-B*, unites with the 10 amperes coming down through *A-B*, delivering 20 amperes in the line *B-D* to the load. This current, returning through *E*, finds its way to the source from which it emanated. The 10 amperes that originated in *B-C* returns to that portion of the winding, entering at *C*. The 10 amperes that came from the original source of supply *F* returns via the wire *G* to the source from which it came. The same result is accomplished as far as the load is concerned as in Fig. 759. If, therefore, as previously stated, both voltages are so low as to make the arrangement safe, or both voltages are dangerous to life, or if there is not much change to be effected in voltage, there is every advan-

tage in the auto-transformer arrangement, Fig. 760, over the plan in the usual transformer shown in Fig. 759.

The K.V.A. capacity of an auto-transformer required in any given case equals

$$\frac{EHT - ELT}{EHT} \times K.V.A. \text{ of the load,}$$

where EHT = e.m.f. of high-tension winding.
ELT = e.m.f. of low-tension winding.

Thus if, as in the preceding example, EHT is 100 and ELT is 50, and the power required by the load is 6 K.V.A.,

$$\frac{100 - 50}{100} \times 6 = 3 \text{ K.V.A.}$$

Thus an auto-transformer of 3-K.V.A. capacity would answer for the necessary transformation with a 6-K.V.A. load, whereas, if an ordinary transformer were employed with the two windings separate, 6 K.V.A. would be necessary.

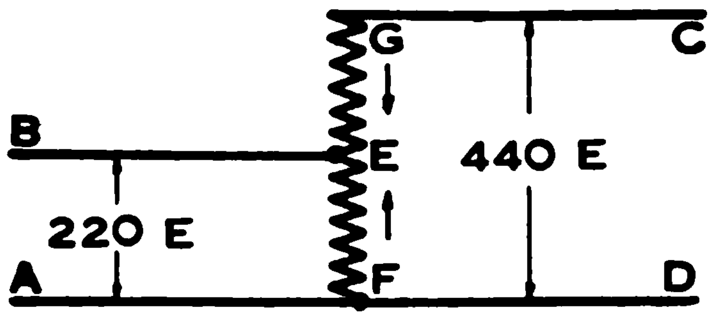


FIG. 761.

The auto-transformer may be used equally well to either raise or lower the voltage. Thus in Fig. 761, if power be supplied at the points A-B at 220 volts, tapped into the end and middle points of a winding, power could be taken off at C-D at 440 volts. This is because current flows through the wire A and into the transformer from F to E, thereby inducing an e.m.f. in the other half of the winding in the direction from G to E. This portion of the winding G-E acts as an auxiliary e.m.f. in series with the source across B-A, and as each is of 220 volts the load connected across D-C will receive 440 volts. If the connections to G-E are reversed as in Fig. 762, the current flowing through F-E induces an e.m.f. in the other portion of the winding in the direction G-E. This e.m.f. is now in opposition to the source across the B-A, and the voltage across C-D

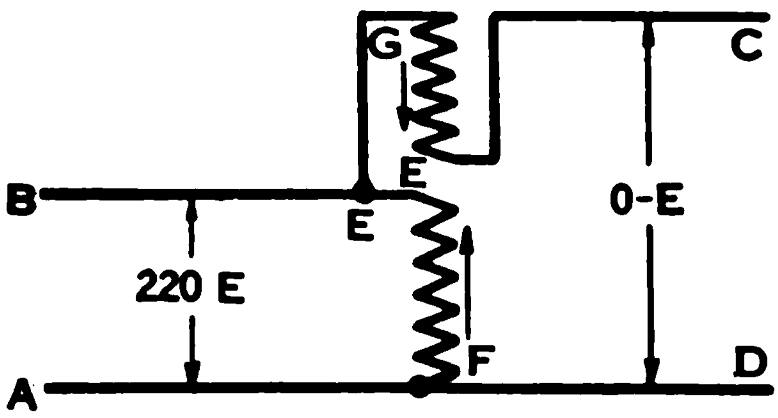


FIG. 762.

is therefore zero. If the relation between the voltage in *G-E* and *E-F* could be altered gradually, an entire range of voltage from zero to 440 volts could be obtained. This is actually effected in the induction regulator designed for varying the voltage in a feeder supplying an alternating-current load.

The induction regulator consists of two windings, Fig. 763, one a secondary *S*, connected in series with the load, the other a primary *P*, in shunt with the line. The primary is mounted so that its inductive relation to the secondary can be varied. As the connections to the primary are of fine wire they are flexible, while, if the secondary were moved, the heavier connections would be stiff and more difficult to handle. The circuits shown constitute an auto-transformer or transformer booster with a variable ratio of transformation. If the primary is rotated 90° in one direction, the voltage on the line will be raised by the amount of e.m.f. induced in the secondary. If the primary is

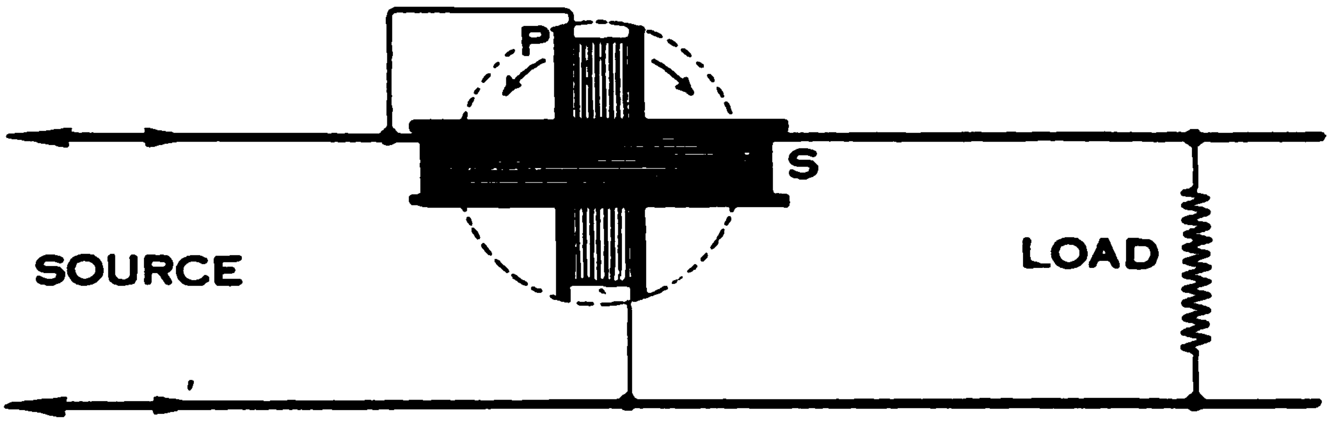


FIG. 763.—Theoretical arrangement of induction regulator.

rotated 90° in the reverse direction, the voltage on the line will be lowered to the extent of the induced e.m.f. in the secondary.

The actual construction of the induction regulator is shown in Fig. 764. The primary *P* is wound upon a pivoted iron core *C* resembling a Seimen's "H" armature. The secondary *S* is placed in slots in a stationary iron member as shown. The relative position of the two coils in this view is the same as in Fig. 763. When the primary is rotated 90° the two windings are parallel with each other, and a maximum voltage is induced. When they are at right angles to each other in the position of minimum induction the coil *S* constitutes a highly inductive circuit which would cause a considerable drop in voltage as the line current passes through it to the load. To offset this self-induction a short-circuited coil *B* is placed in the primary member with its plane at right angles to that of the primary coil. In

the position shown in Fig. 764 it is parallel with the secondary coil and acts as a short-circuited secondary to that member. Its reaction therefore neutralizes the self-induction of the

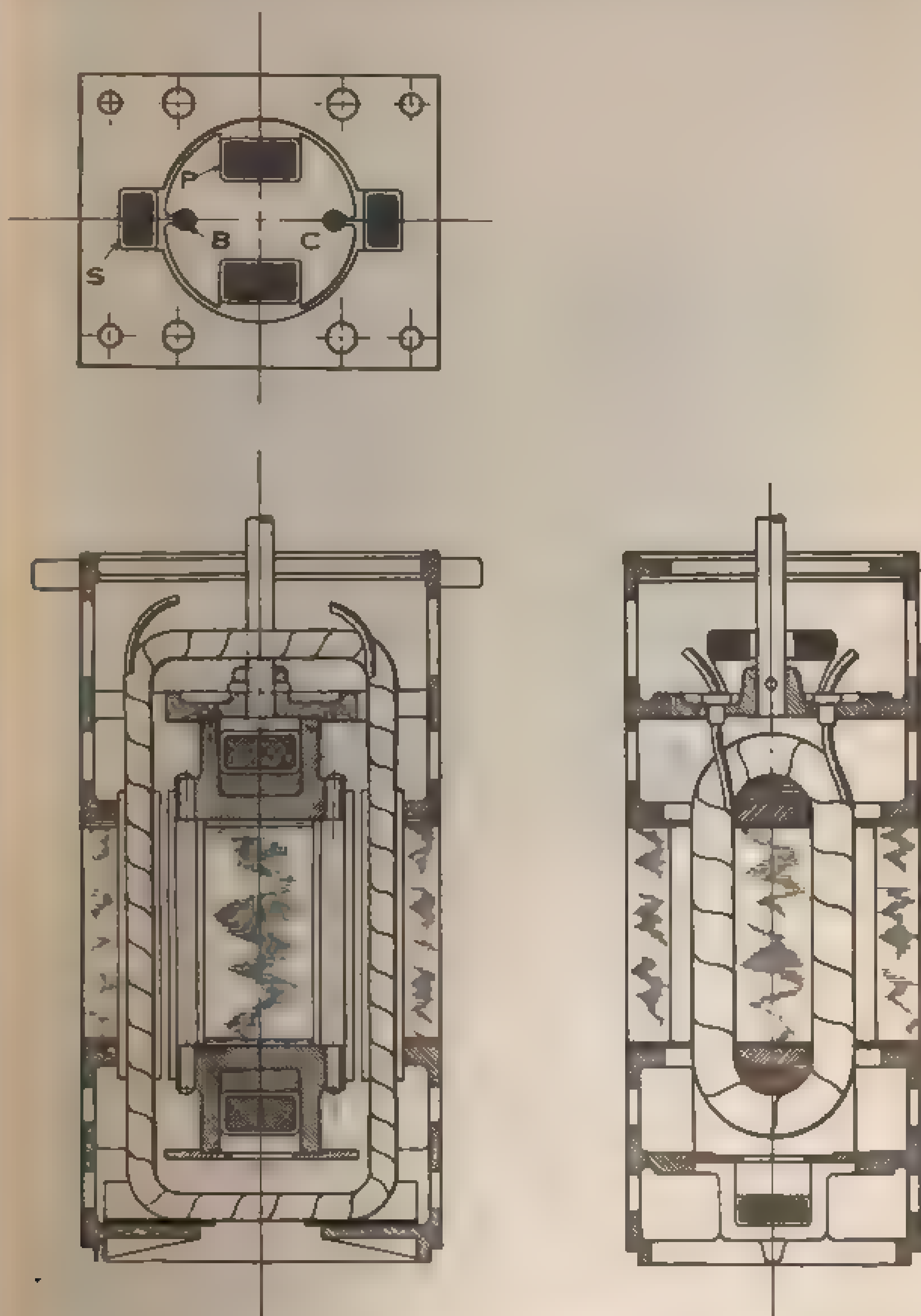


FIG. 764.—Plan and sectional view of a single-phase induction regulator designed by the General Electric Company.

secondary. As it is at all times at right angles to the primary, it never has any voltage induced in it due to that member. In the position shown, the current in the short-circuited coil reduces the reactance of the secondary winding to practically zero.

The position of the primary coil may be controlled by hand or automatically. Usually a small *A-C* motor is placed upon the top of the regulator case connected through a worm gear to the movable primary. This motor is connected in circuit by means

Fig. 765.—Retaining case and inside construction of General Electric induction regulator with motor for rotating primary.

of a contact making voltmeter, which causes the motor to rotate the primary in either direction, as desired.

Fig 765 shows the retaining case, usually filled with oil, and the regulator with operating motor on the top. This type is built by the General Electric Company.

Instead of rotating one of the windings with respect to the other, both windings may be stationary and a commutating switch employed to connect the line to the various points on the

secondary winding. This is called a compensator type of voltage regulator. It accomplishes the same result as the induction type. Both are forms of auto-transformers.

A simple scheme of auto-transformer connection for giving a two to one ratio of voltages is shown in Fig. 766. The low-tension windings only of three transformers are used. The high-tension windings are taped up. Usually three such windings are connected in Δ and tape taken from the middle points of each winding. The application of three-phase, 440 volts, to the points *A-B-C* will enable three-phase, 220 volts, to be drawn from the points *A′-B′-C′*. The current available in each low-tension line will be twice the current supplied from the high-tension lines. It is important to note in this case that the direction of phase rotation in the two Δ's is opposite. This is

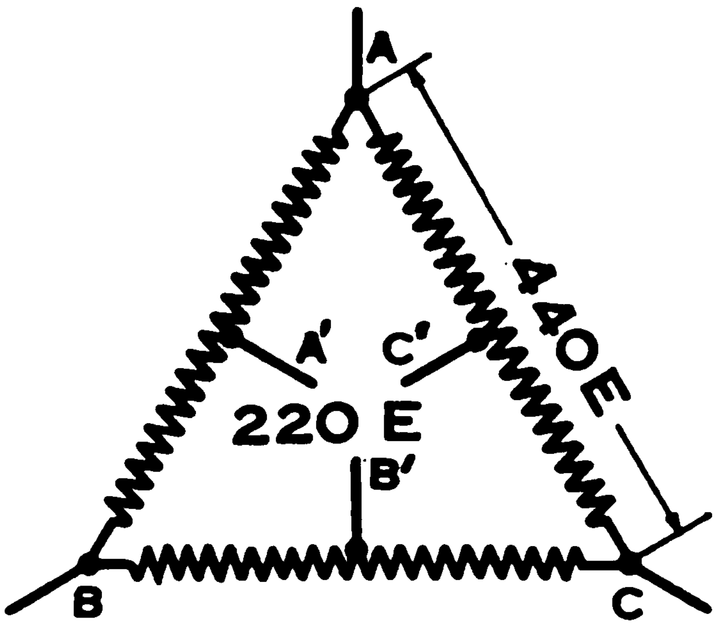


Fig. 766.

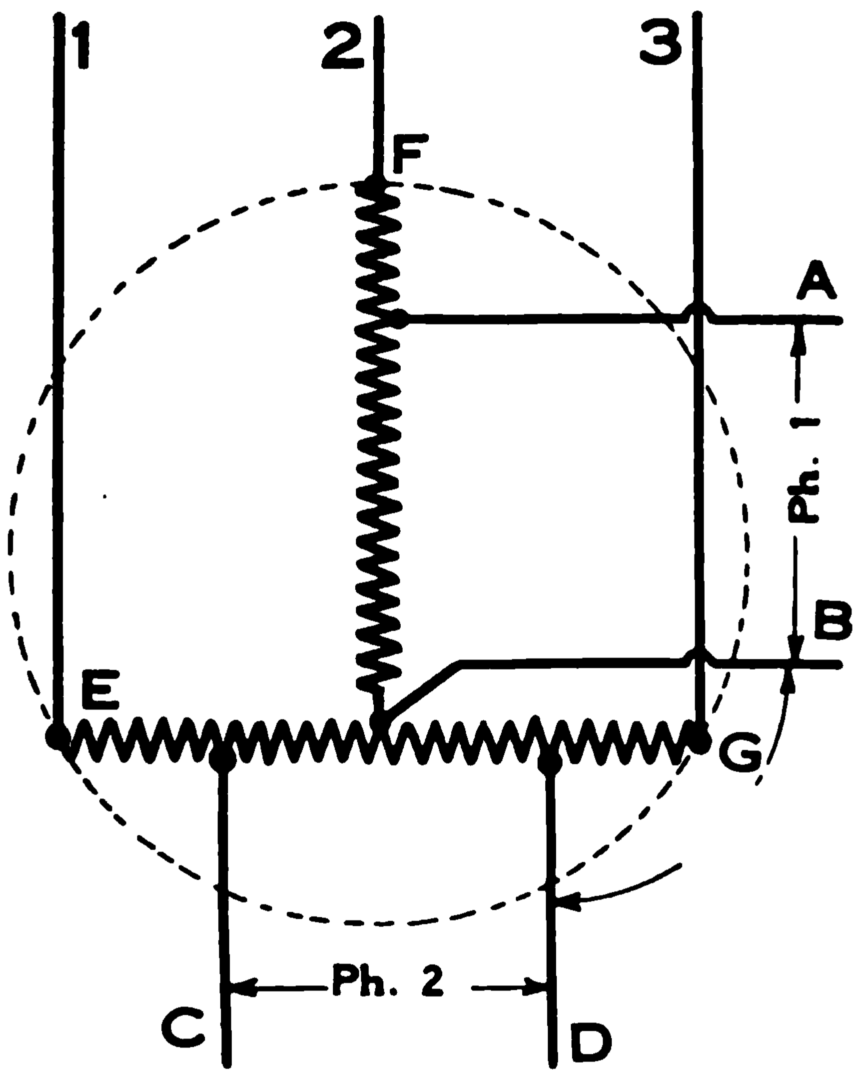


Fig. 767.

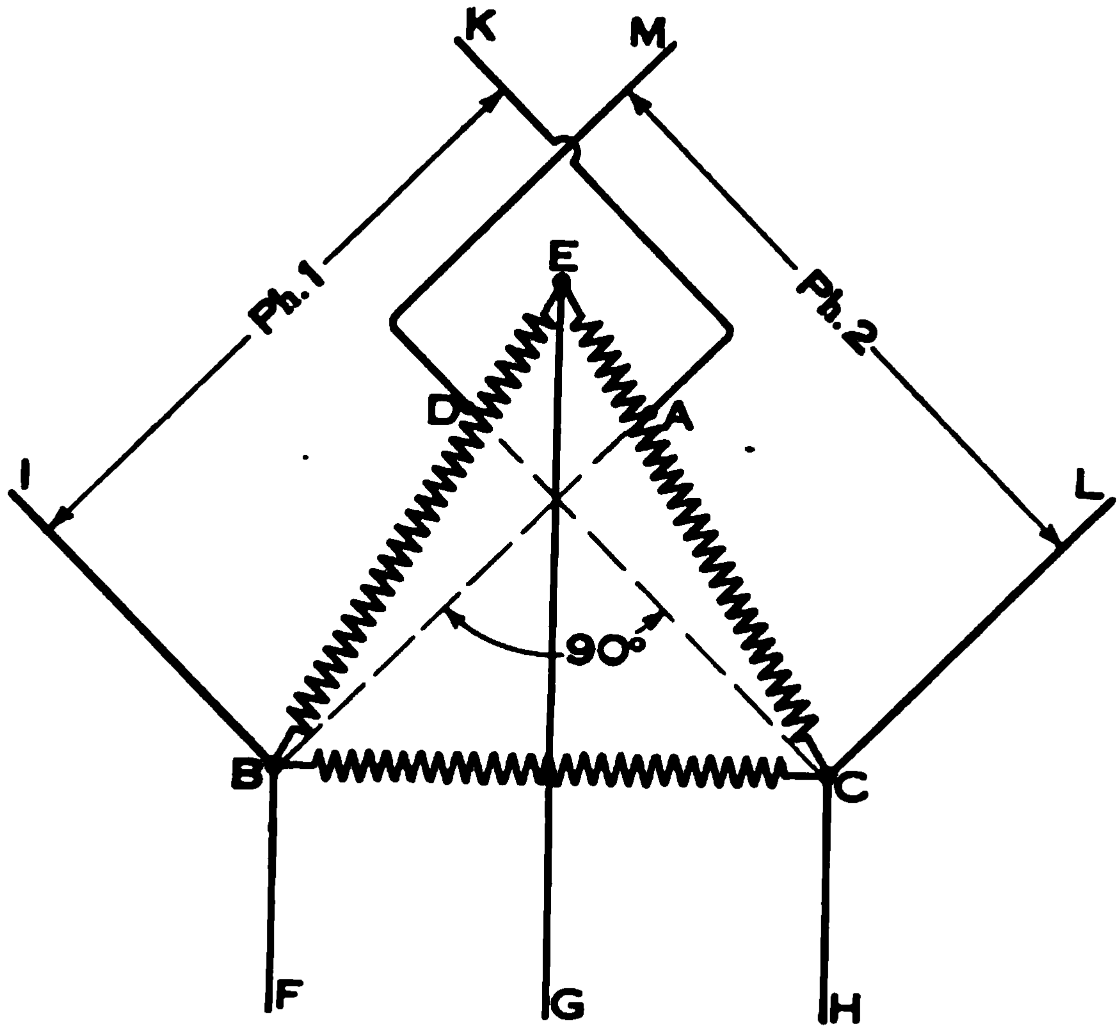


FIG. 768.

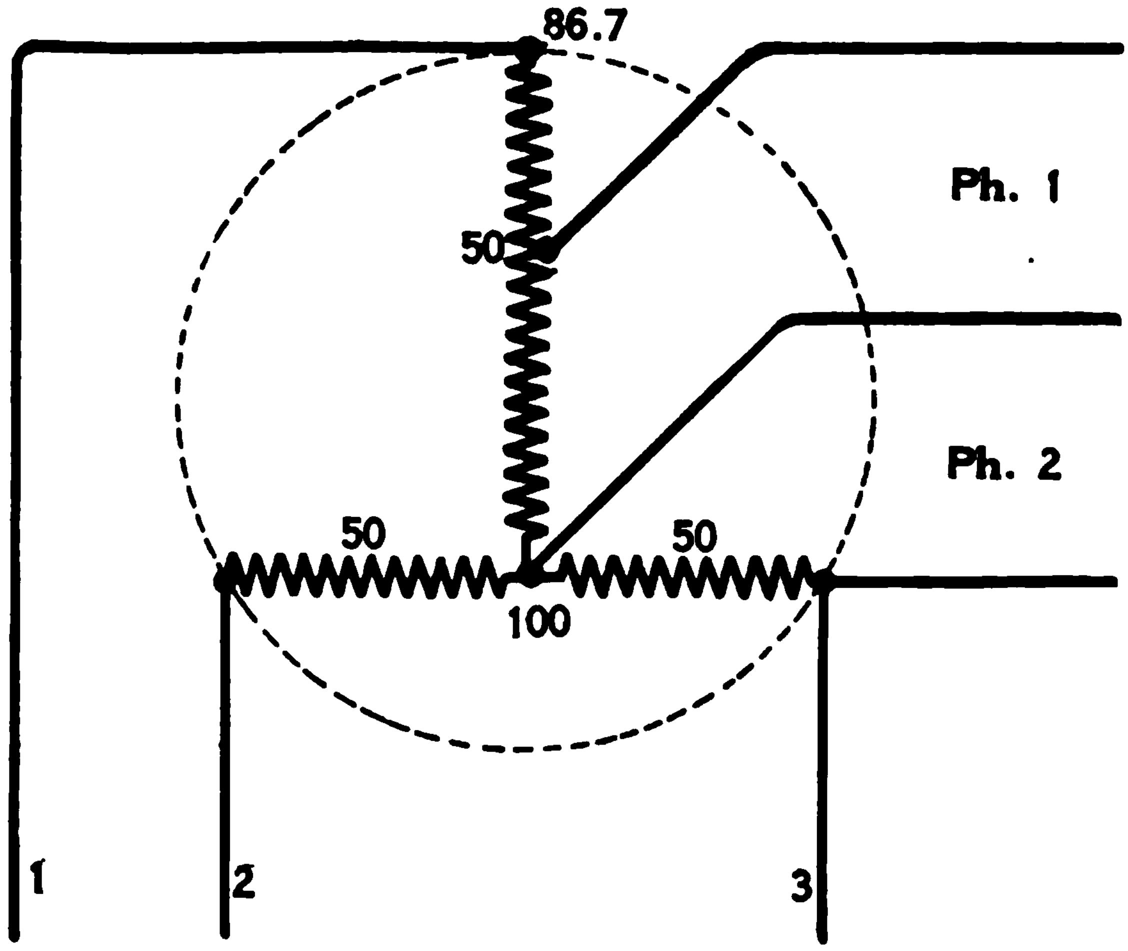


FIG. 769.

due to the fact that the second Δ is upside down or 180 degrees away from the first. When this arrangement is used to obtain a 50% voltage tap for starting motors, two of the leads must be interchanged when passing from half potential to full potential, otherwise the motor would reverse.

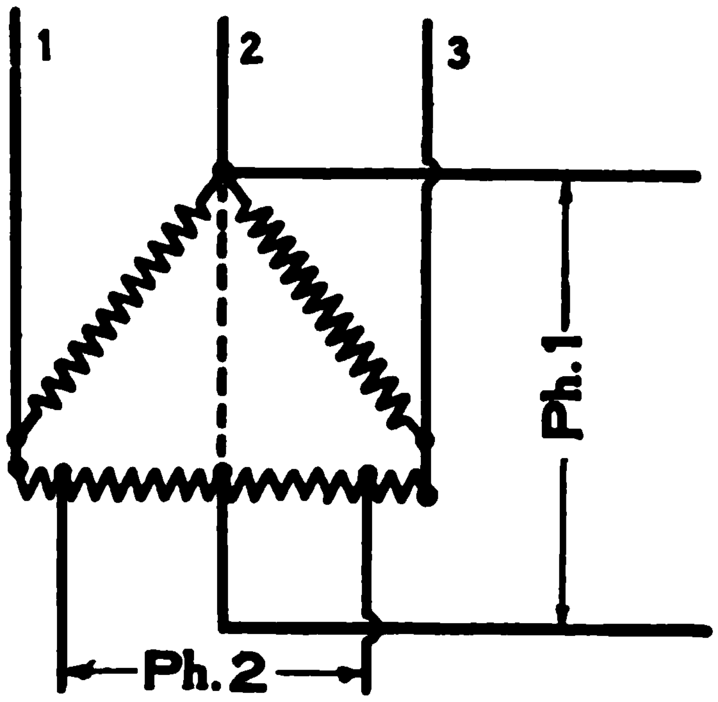


FIG. 770.

A method of securing a two-phase to three-phase transformation by the aid of auto-transformers which will effect an economy in material is shown in Fig. 767. Two auto-transformers, having the relations of 86.7 to 100 to each other, are connected in T. A two-phase source supplies current through the wires *A-B-C-D*. From the points *E-F-G*, three alternating currents, 120° apart in phase, may be obtained. With the usual ratio in such transformations, a total capacity of 7 kilowatts in the upright and 14 kilowatts in the cross bar of the

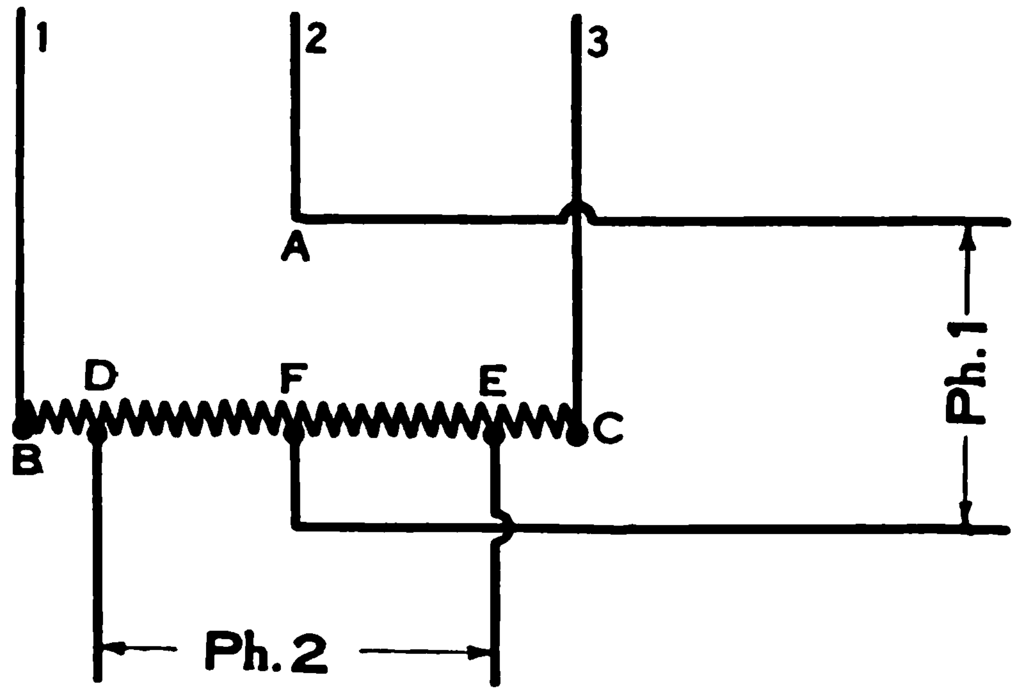


FIG. 771.

T will enable 100 kilowatts to be passed from the two-phase source to the three-phase load.

Another ingenious three-phase to two-phase transformation is shown in Fig. 768. Here a Δ-connected bank of transformers has a tap taken at a point *A* in one transformer and at *D* in another transformer, these taps being so related to each other

that the line A-B is at right angles to the line C-D. Then when a three-phase supply feeds the bank at F-G-H, two-phase currents may be drawn from I-K and L-M.

A common auto-transformer connection for changing two-phase three-wire to three-phase is shown in Fig. 769. The two-phase voltage here must be just one-half the three-phase.

Another two-phase to three-phase arrangement employing Δ connections is shown in Fig. 770.

A most unusual connection for changir.g two-phase to three-phase with only one transformer is shown in Fig. 771. The theory of this connection, referring to Fig. 772-A, is as follows:

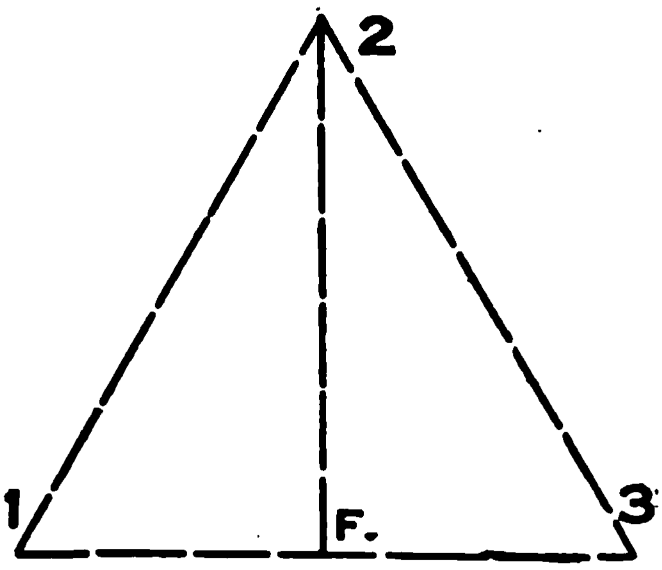


FIG. 772.

The phase relation between the three-phase lines 1, 2 and 3 is 60°. If a transformer is connected between points B and C, the vector direction of its voltage will be along the line B-C establishing the phase direction of phase No. 2. A connection between points 2 and F will establish the phase direction for phase No. 1. The phase relation between phase No. 1 and phase No. 2 will obviously be 90° as the point F is taken at the exact middle of B-C. Phase No. 2 is taken from taps D and E which are so placed that the voltage across D-E is 86.7% of the voltage across B-C. The two-phase voltage in this connection is obviously 86.7% of the three-phase voltage. Many other auto-transformer connections are possible by which a polyphase system may be converted and voltage changes effected with great economy in material.

SECTION XV CHAPTER VII

TRANSFORMERS

AUTO TRANSFORMERS

1. What is meant by an "auto" transformer? What are its advantages and disadvantages? When should it be used, and when should it not be used? Under what conditions is it most advantageous to use an auto transformer?

2. If the high tension voltage of a system is 2,200 and the low tension side requires 550 volts and the load demand on the low tension side is 160 k.w., what will be the k.v.a. capacity of an auto transformer for the purpose?

3. Explain the principle of an "induction regulator." Where is it used? How is it controlled? How is the reactance of the secondary neutralized?

4. Sketch a Δ connection of the low tension windings of three single-phase transformers to produce a two to one ratio as auto transformers.

5. Sketch a two-phase to three-phase connection of an auto transformer. What are the voltage ratios established?

6. Sketch a single-phase transformer and the connections necessary to convert a two-phase to three-phase.

7. Can polyphase power be tranformed by the aid of a single transformer having a single magnetic circuit? Why?

TRANSFORMERS

PHASING OUT OF TRANSFORMERS

Paralleling Transformers on Single-Phase Circuits

When two or more transformers are to be paralleled on both the high-tension and low-tension sides, it is necessary to test the instantaneous polarity of the secondary of one before it is paralleled with the others to avoid short-circuiting the line. Thus in Fig. 773, transformer *A* is assumed to be in circuit with the high-tension mains and its low-tension winding connected to the low-tension mains. Transformer *B* may now have its high-tension terminals connected to the high-tension mains without any testing. One end of its low-tension winding may also be connected to a low-tension main, but before the other

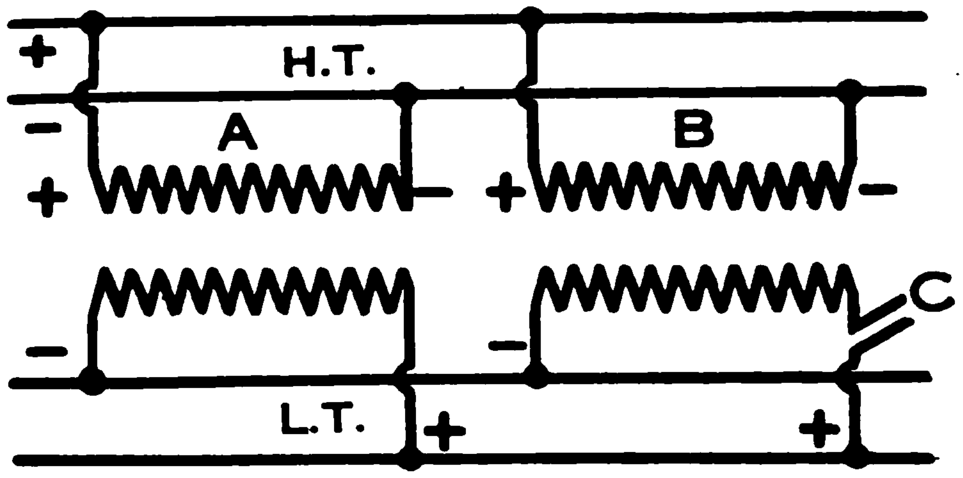


FIG. 773.—Test to determine relative instantaneous polarity of low-tension windings of two transformers.

end is connected a test must be made between the points at *C* to determine whether or not its polarity at a particular instant is right. A voltmeter, fuse or lamp bank may be employed for this purpose. If a voltmeter is connected at these points it will indicate twice the normal voltage if the connections are wrong, for the two low-tension windings would then be in series. If the connections are right, zero voltage will be indicated. Under the latter condition the voltmeter may be removed and the gap closed. If a fuse equal to the rated capacity of the transformer be inserted in place of the voltmeter, it will blow if the connections are wrong but will not be affected if the connections are right. When testing with a voltmeter, if a load is on the low-

tension circuit, a slight voltage may be detected across *C* due to the difference in potential between the generated voltage in the transformer *B* and the delivered voltage of the transformer *A*. A lamp bank may be also used for testing but should have enough amps in series to withstand double the transformer's voltage. If the lamps are lighted to full candle-power, a wrong connection is indicated. If they do not light at all, the connections are correct.

Paralleling Transformers on Polyphase Circuits

To put three single-phase transformers in Δ and connect in parallel with another bank already in parallel on the high-tension side, proceed as follows:

Connect all three high-tension sides in parallel on one phase

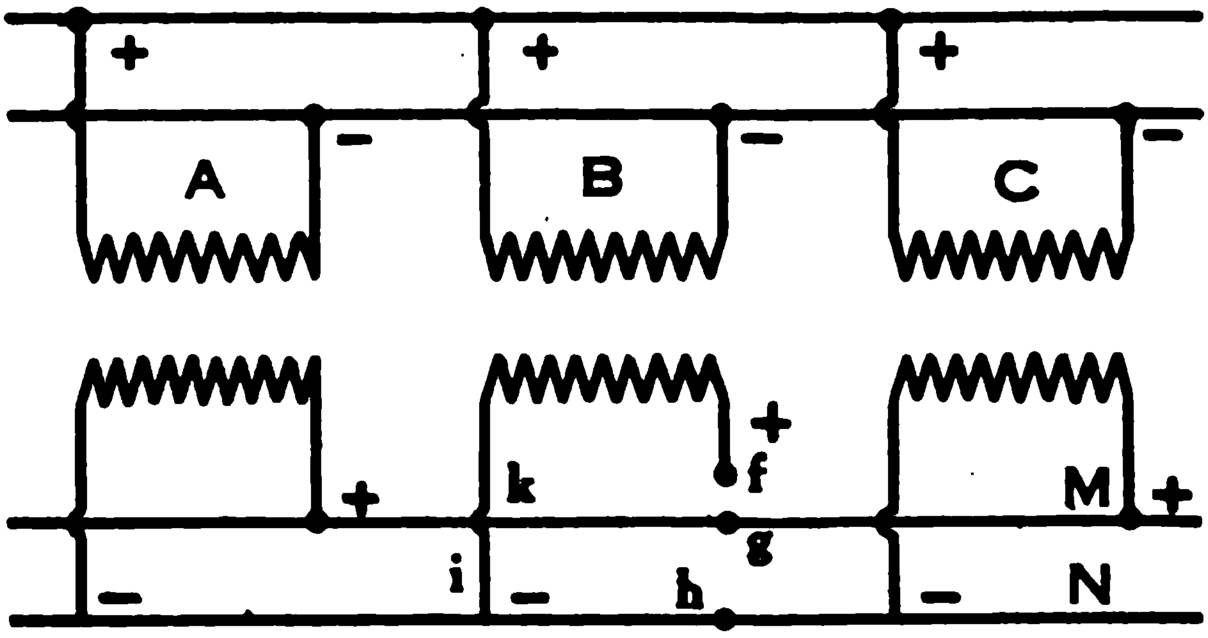


Fig. 774.—Identification test for terminals of high-tension and low-tension transformer windings.

of the high-tension source, Fig. 774. Tag all three leads on one high-tension side "+."

Tag all three leads on the other high-tension bus "—."

Connect both low-tension leads of one transformer, *C*, to the low-tension bus, *M-N*. Test out the low-tension leads of the other two transformers and parallel as in single-phase test in Fig. 773. When all three low-tension windings have thus been placed in parallel:

Tag all three leads on one low-tension bus "+."

Tag all three leads on the other low-tension bus "—."

Now to put the three high-tension windings in Δ, disconnect from the high-tension mains and connect the three high-tension transformer windings, + to —; + to —; + to —, as in Fig. 775.

If it is desired to place these windings in Y instead of in Δ three correspondings ends should be tied together and the other three corresponding ends led to the high-tension mains as in

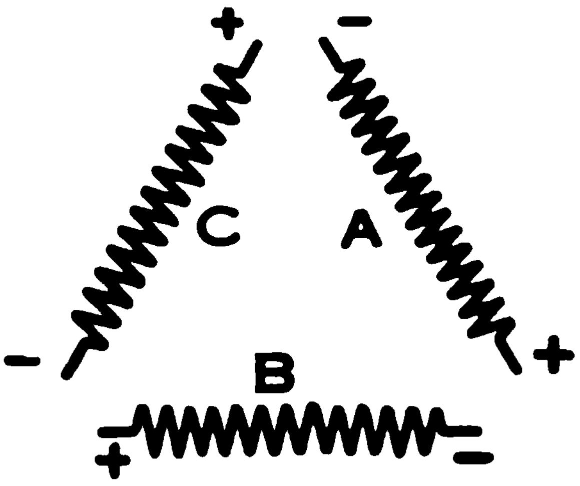


FIG. 775.

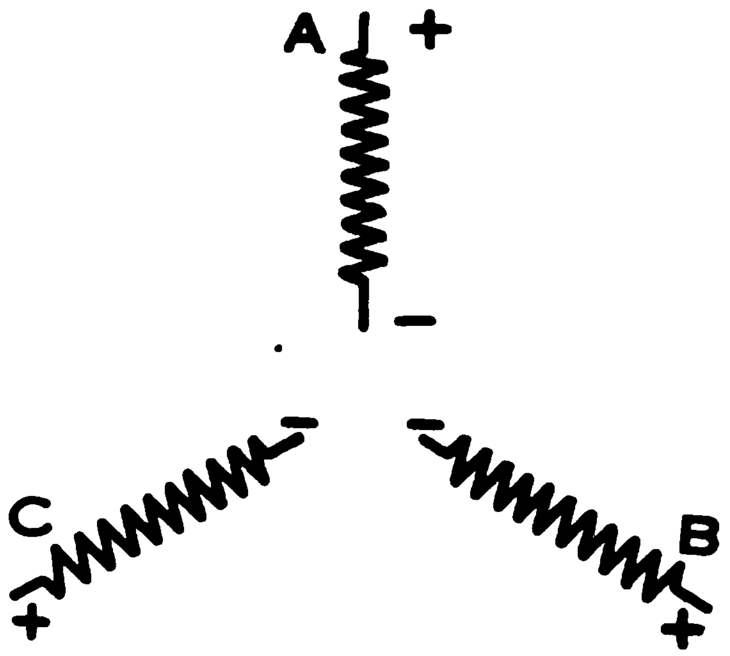


FIG. 776.

Fig. 776. Put the low-tension winding in Δ or Y in the same manner.

Then put the high-tension Δ in circuit with the high-tension source as at *B*, Fig. 777.

Next test the original low-tension source represented by the points 1, 2 and 3, Fig. 777, against the secondary Δ of the newly connected bank, represented by the points *C*, *D*, and *E* by means of a voltmeter as shown in Fig. 778. When two points such as

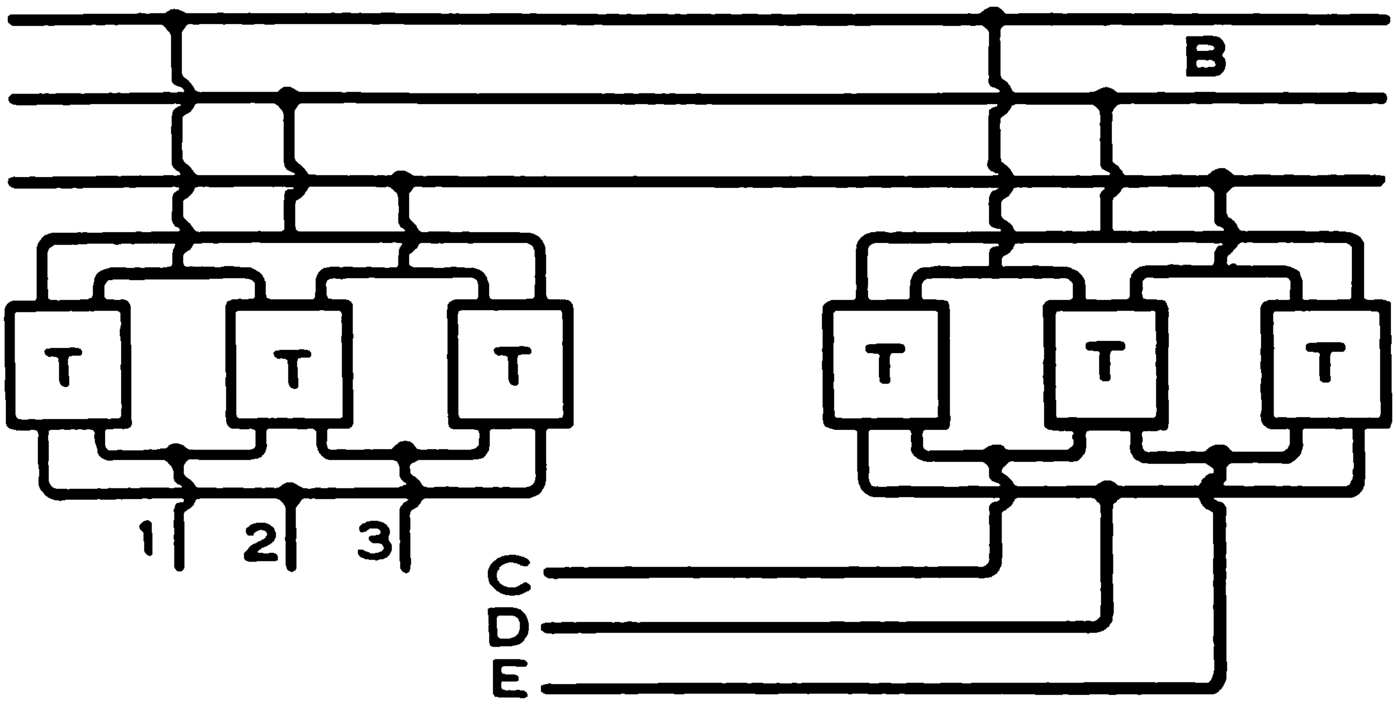


FIG. 777.—Paralleling three newly-installed single-phase transformers with three others already connected on three-phase system.

1 and *C* are connected together, any of the two points across which no potential difference is indicated on the voltmeter, such as 2 and *D*, may be connected together permanently.

Another method of phasing out three single-phase transformers

individually to be connected in Δ and in parallel with a composite three-phase transformer already in line is shown in Fig. 779. *D* is the composite transformer and *A*, *B* and *C* are the single-phase transformers.

Connect the high-tension terminals in Δ. This requires no

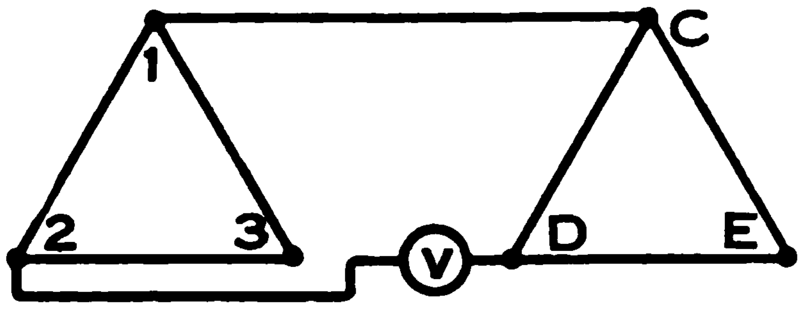


FIG. 778.

testing whatever. They are simply connected in a closed loop. Next connect this Δ to the high-tension source.

Taking the terminals to transformer *A*, numbered 4 and 5, these should now be tested against the various terminals 1, 2

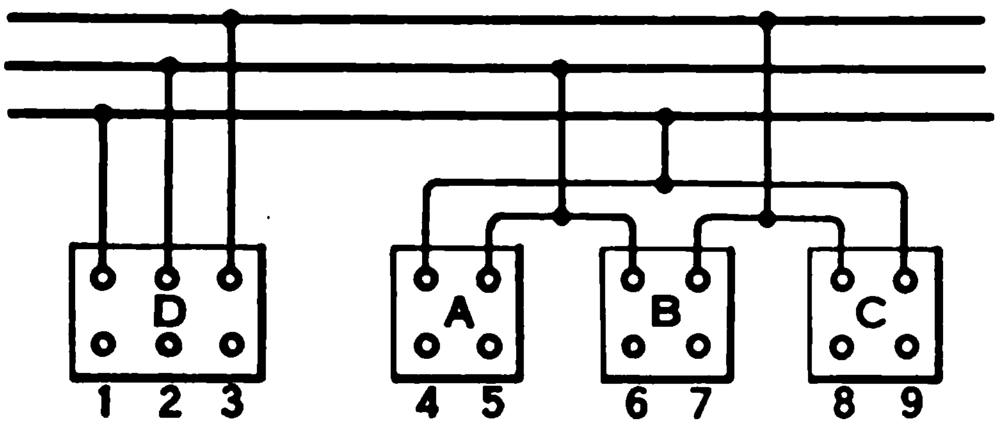


FIG. 779.

and 3 of *D*, as in Fig. 780, with a voltmeter having a range of twice the voltage of one phase. If 4-5 has the same direction as 1-2, then 2 and 5 being connected, when the voltmeter bridges

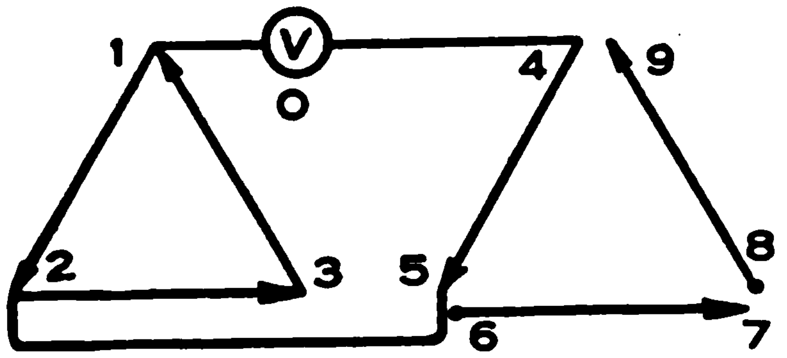


FIG. 780.

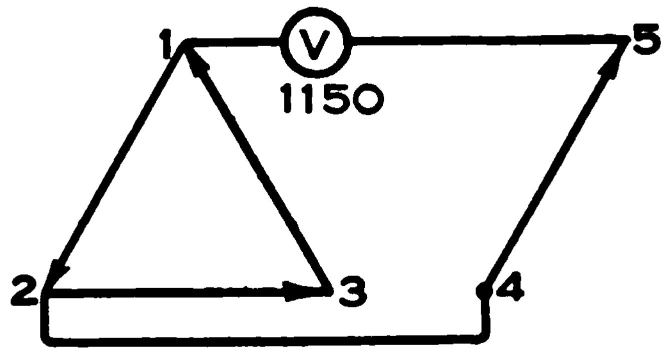


FIG. 781.

the gap between 1 and 4, no difference of potential will be indicated. This shows that transformer *A* is the **right** phase and is matched in the **right** direction with the **proper phase** of transformer *D*. If, however, the terminals of *A* were reversed, giving

the direction 4-5, Fig. 781, the circuit, being completed through 1-2-4-5, would throw the e.m.fs. of these two phases in series. If the voltage of each side of the Δ were 575, the voltmeter would now read 1,150 volts. This is an indication that *A* is the

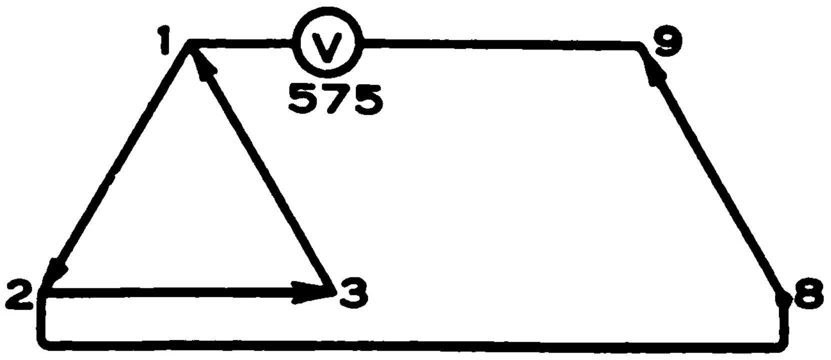


FIG. 782.

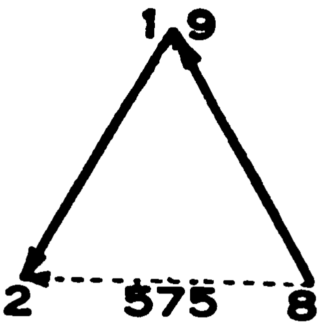


FIG. 783.

proper phase but connected in the **wrong direction** with phase 1-2 of *D*.

Instead of the terminals of transformer *A*, those of *C* numbered 8 and 9 might have been the first one to be tested across one leg of the composite Δ, 1-2, Fig. 782. If the circuit is completed through 1-2, 8-9 and the voltmeter, the phase relation of 8-9 to 1-2 will be as in the vector diagram, Fig. 783. These two voltages 60° apart give the e.m.f. 8-2, or 575 volts. This is the same as the e.m.f. of one phase. This indicates that the **wrong**

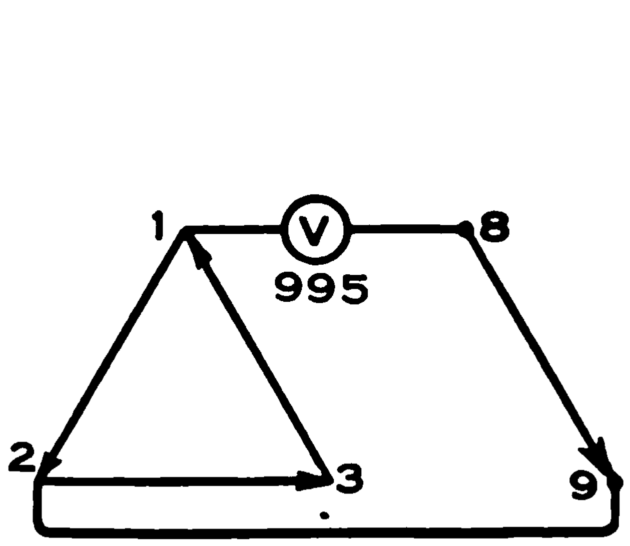


FIG. 784.

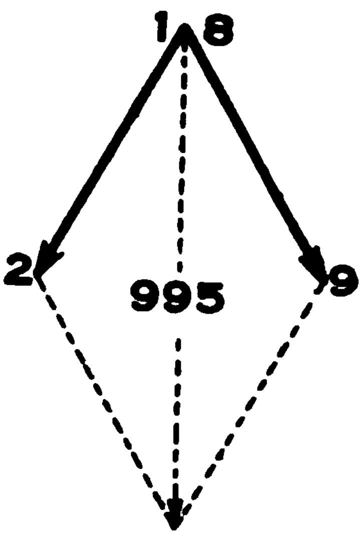


FIG. 785.

phase is now matched across 1-2. Should the connections of *C* have been reversed, the direction of the voltage would be 8-9, Fig. 784. When the circuit is now completed through 1-2, 9-8, the voltage, being in the same direction in these two windings, would give the vector Fig. 785, and the voltmeter would read 995 volts.

Should the transformer, *B*, be matched against the side 1-2 of *D*, as in Fig. 786, when the circuit is completed through 1-2, 7-6,

the vector, Fig. 787, would be obtained. The geometric sum of these voltages, 1-2 and 6-7, is the voltage of one phase, 575 volts. This again indicates that transformer *B* is the **wrong phase** to parallel with 1-2 of *D*. Should the connections of *B* to *D* be reversed, the e.m.f. of 6-7 with respect to 1-2 would be shown in Fig. 788. The geometric summation of these voltages

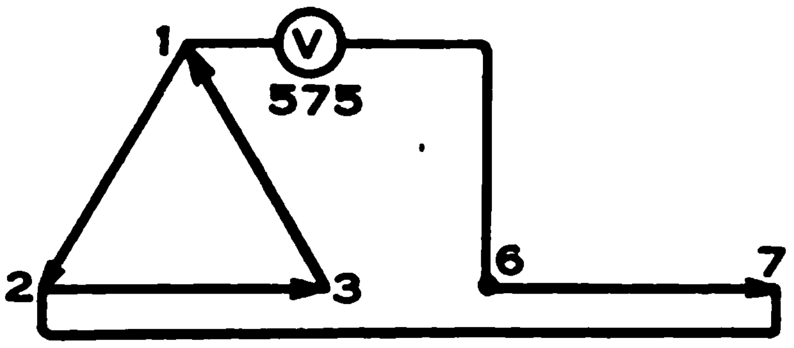


FIG. 786.

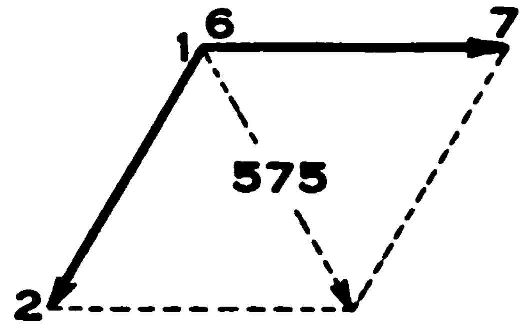


FIG. 787.

is shown in vector, Fig. 789. This would be 995 volts. This, again, is the **wrong phase** and with **connections reversed** compared with the preceding case.

With a phase voltage of 575, it is thus evident that when one of the single transformers having the right phase relation is matched against the corresponding phase of the composite transformer, the voltmeter indications will be either zero, which is right, or twice the phase voltage, which is wrong.

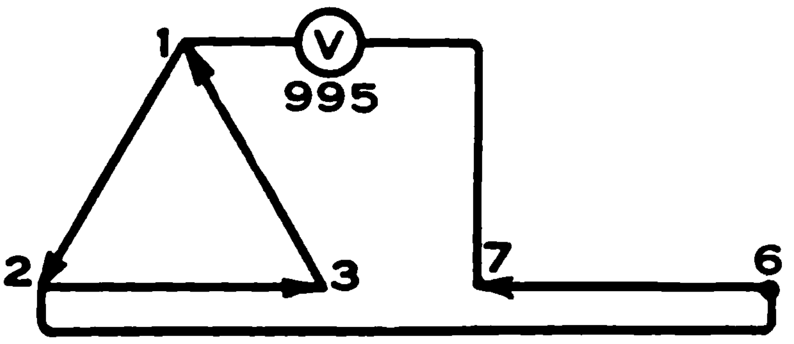


FIG. 788.

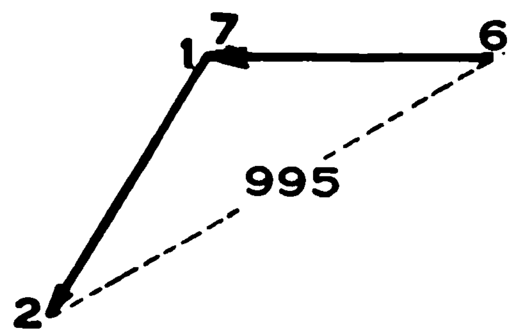


FIG. 789.

Each of the other two single-phase transformers, when matched against a single phase of *D*, will give one of two voltages according to the particular direction of this e.m.f., either 575 or 995. Both of these readings indicate the wrong phase, the 575 indications being obtained with the wrong phase in one direction, and the 995 indication with the wrong phase reversed. Each phase should be tested until it is matched against the correct phase of the composite transformer and a zero indication of voltages obtained as in Fig. 780.

When it is desired to parallel two alternators of the same

voltage in a generating station, the original test to determine the correct phase rotation can be very simply made by the aid of an induction motor. Assume that the alternator *A*, Fig. 790, is already connected to the bus bars *D*, and the alternator *B* is to be tested out to ascertain with which of the bus bars the

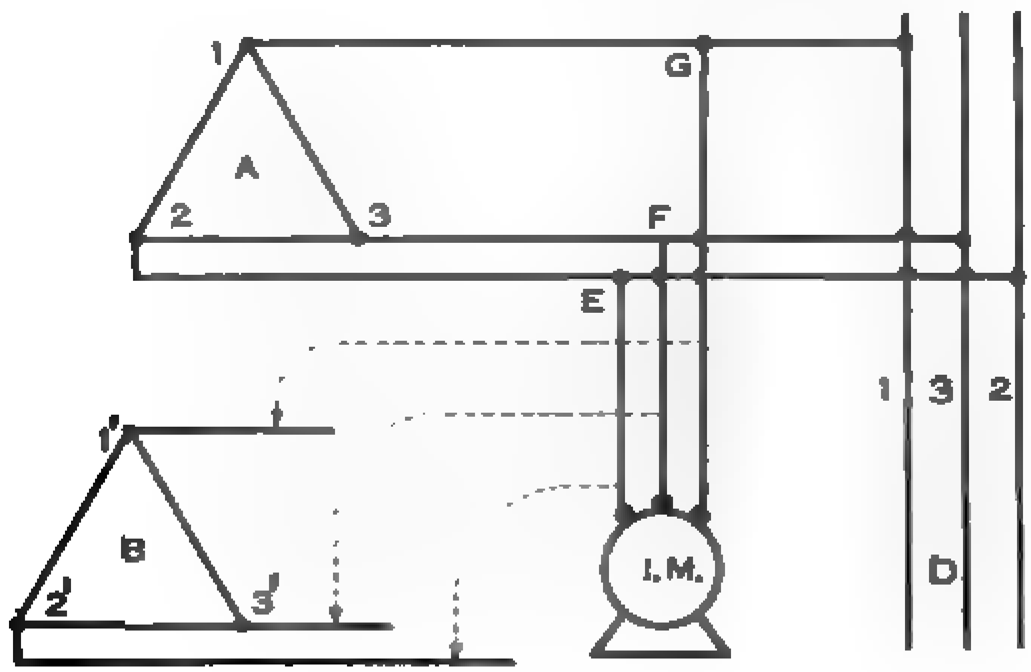


FIG. 790.—Induction motor test to determine direction of phase rotation.

wires 1'-2'-3' should be connected. The induction motor *IM* is first connected across the alternator *A* as shown. The direction of rotation is noted The wires *E-F-G* are now disconnected and swung down to the terminals 1'-2'-3'. If the induction motor rotates in the same direction, as before, then 1' may be connected to bus 1, 2' to bus 2 and 3' to bus 3. If, however, the motor should

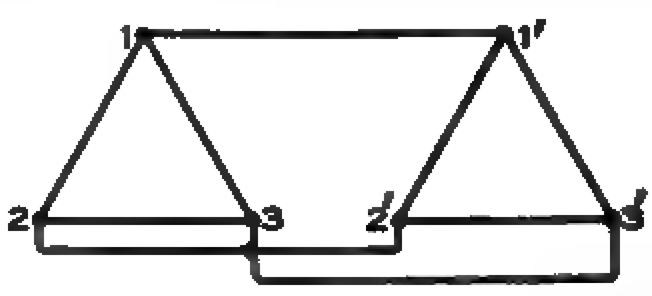


FIG. 791.

run in the reverse direction, it would indicate a reversal of phase rotation in *B* compared with *A*. To correct this reversal any two of the wires 1'-2'-3' should be interchanged or cross-connected with respect to the bus bars 1-2-3 Thereafter, when the alternators are properly synchronized, they may be operated in parallel.

If the sources are entirely independent as in the case of the two alternators, it is not absolutely necessary to have wire 1 connected to 1′, wire 2 to 2′ and wire 3 to 3′, as in Fig. 791, as no harm will result from advancing these connections—thus 1′ to 2, 2′ to 3, 3′ to 1.

If, however, these two Δ's were derived from the secondary sides of two banks of transformers whose high-tension sides were already connected in parallel, as in Fig. 792, this advance of connections above suggested could not be made, as it would result in a short circuit on the high-tension side. Thus, in Fig. 792, 1′ has been advanced to 2, 2′ to 3 and 3′ to 1. Notwith-

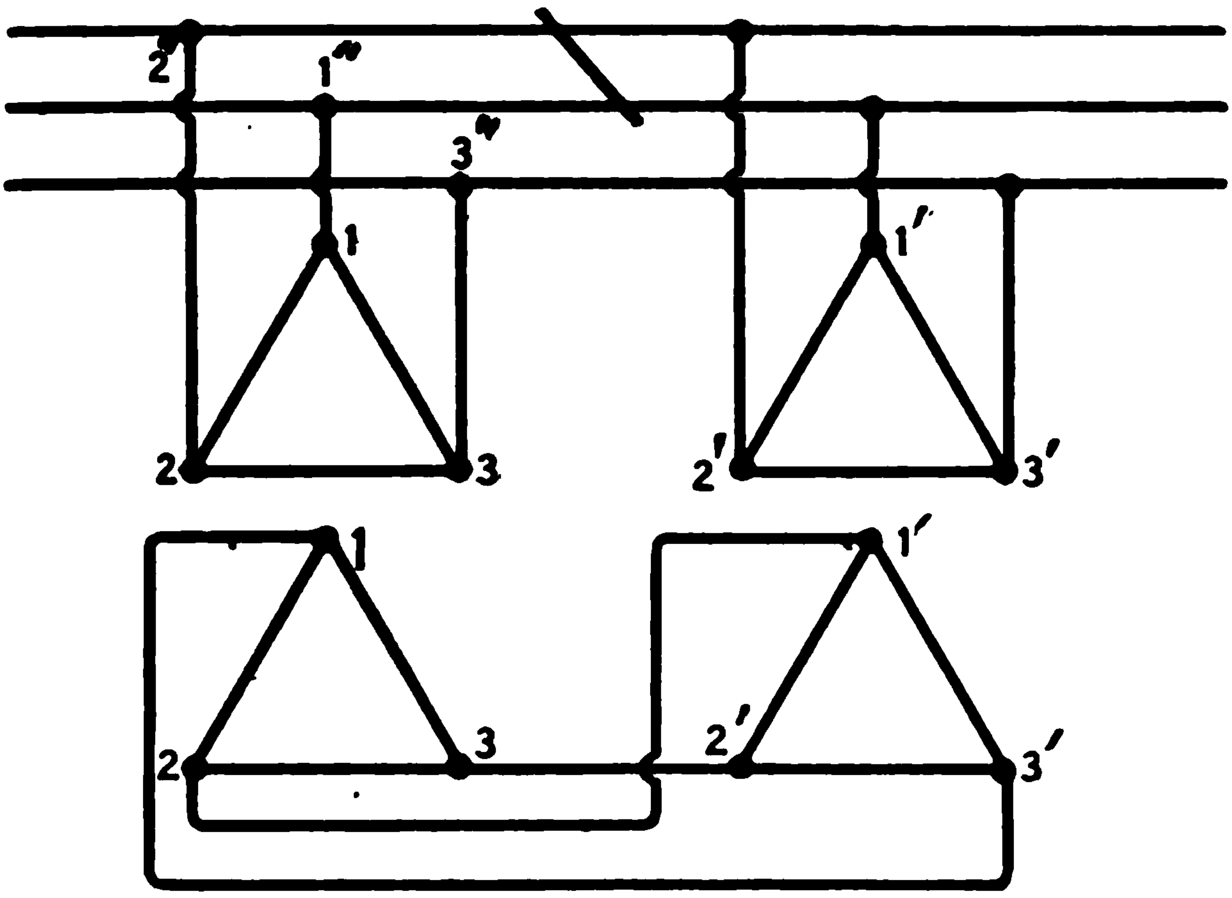


Fig. 792.

standing that the direction of phase rotation is the same in these two Δ's, this connection is handed back through the transformers to the high-tension windings and in effect connects 1′ to 2 on the high-tension side. This means that the high-tension winding which leads to bus 1″ is connected to the high-tension bus 2″, and therefore constitutes a short circuit on the high-tension mains.

Thus the induction motor would be useless in such a case, for it is not sufficient to know the direction of phase rotation alone, but each phase of the low-tension Δ must be matched against the corresponding phase in the Δ of the other transformer.

Transformers which are connected in Y on the high tension and in Y on the low tension may be placed in parallel with transformers of the same delivered voltage which are connected

in Δ on the high-tension side and Δ on the low-tension as in Fig. 793.

Mixed connections of Δ to Y, however, could not be paralleled with either Y to Y or Δ to Δ, as illustrated in Fig. 794. Here

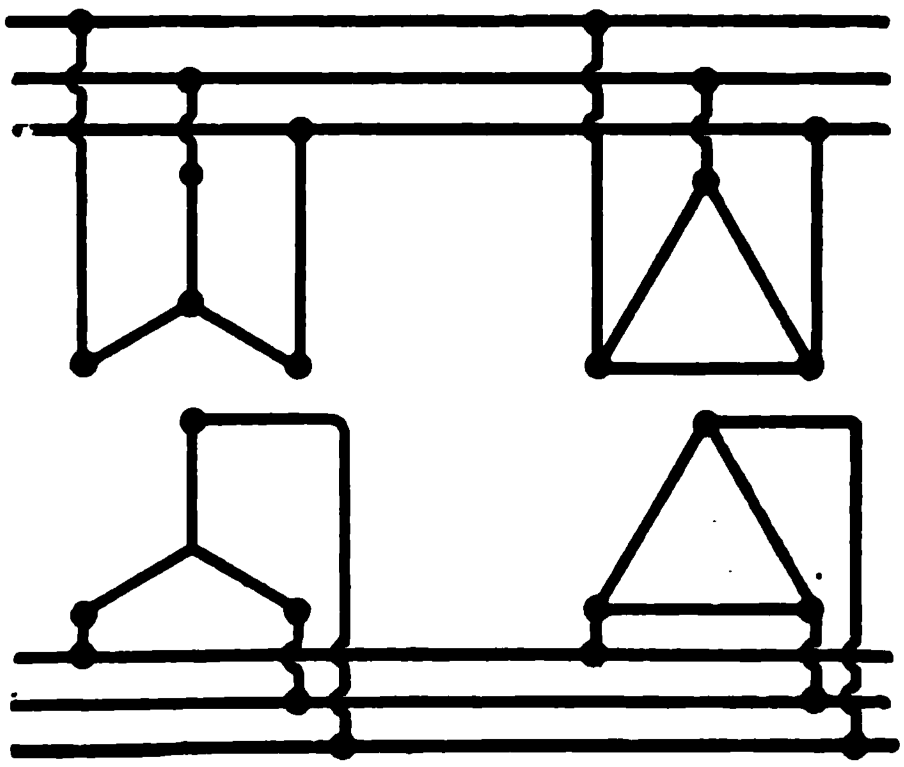


FIG. 793.

transformer No. 2 is connected in Δ to Δ. Transformer No. 1 is connected Y to Δ. Now phase 3 of the low-tension Δ of transformer No. 1 is in phase with phase *A* of the high-tension side. Phase 1 is in phase with *B*. Phase 2 is in phase with *C*.

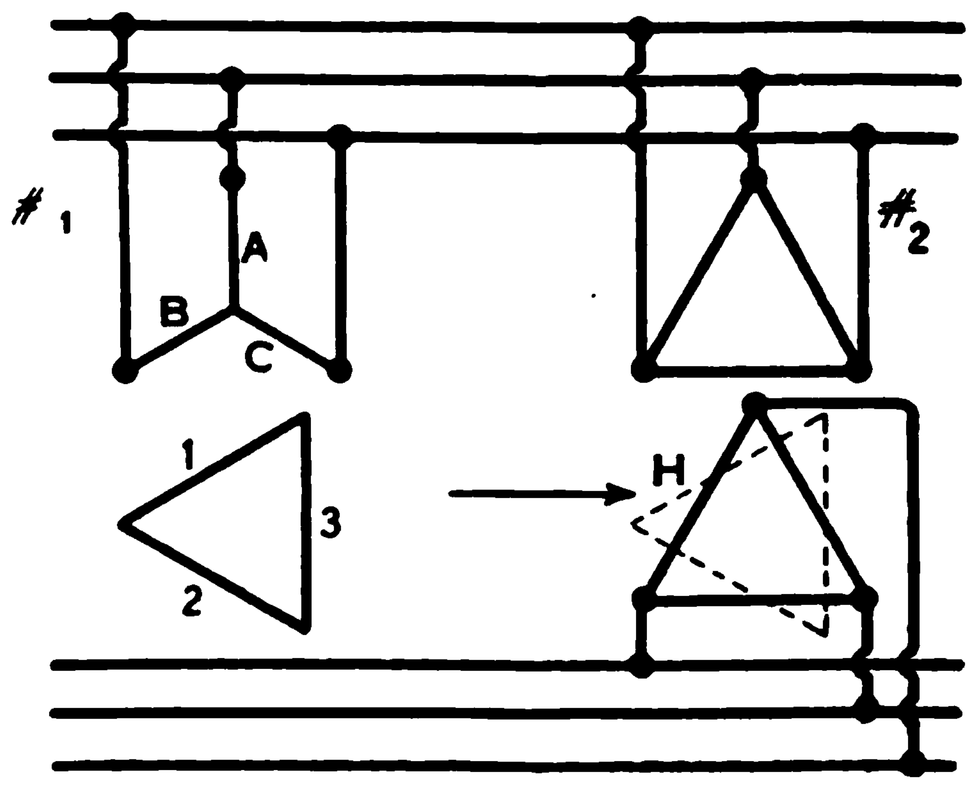


FIG. 794.

The effect in transformer No. 1 is to thus tilt the low-tension Δ through an angle of 30° as shown in dotted lines at *H* in tra former No. 2. It is evident that this angle of 30° low tension of No. 1 and the low tension of N them from being operated in parallel on

SECTION XV CHAPTER VIII

TRANSFORMERS

"PHASING OUT" OF TRANSFORMERS

1. If two single-phase transformers were in parallel on the high tension side, how would you test out the low tension side to place them in parallel also, and be sure that they were not in series?

2. If you had two three-phase sources of equal potential, which you wished to place in parallel, how would you determine whether or not the direction of phase rotation were the same?

3. In the above case, could you place the two systems in parallel, if the direction of phase rotation were not the same?

4. If the direction of phase rotation in the above case for the two sources were not the same, how would you make it the same?

5. How would you test out a bank of three single-phase transformers so that they may, with absolute certainty, be correctly connected in parallel with a three-phase composite transformer of equal voltage?

6. What would be the effect of advancing the points of contact in the same phase direction between the secondary Δ and one set of transformers and the Δ of another set, the primaries already being in parallel?

7. Can a Δ to Δ bank of transformers be paralleled with a Y to Δ bank delivering the same voltage? Why?

TRANSFORMERS

INSTRUMENT TRANSFORMERS

It is not practical to use a coil-wound voltmeter with resistance in series on high voltage A. C. circuits, because of the excessive insulation which would be required and on account of the large amount of resistance necessary in circuit with high voltages and the very considerable energy wasted therein.

It is also not practical to use a shunt strap and a milivoltmeter to measure the current on an A. C. circuit, because the impedance of a shunt strap varies with the frequency of the current passing through it. Its resistance may be fixed by using a zero temperature coefficient resistor, but its reactance will always vary with the frequency of supply. Consequently the total impedance will vary. Thus if a milivoltmeter connected in shunt with such a strap indicated 10 amperes with a current of given frequency, should the frequency change, the instrument would alter its indication even though the current were the same.

Indications of both voltage and current on such lines are obtained through the medium of instrument transformers. There are two reasons for their use:

First: Station operators are protected from contact with high-voltage circuits.

Second: The instruments may be constructed with a reasonable amount of insulation and a reasonable current-carrying capacity.

The function of instrument transformers is to deliver to the instrument a current and a voltage which shall always be proportional to the primary current and voltage and which shall not exceed a safe potential above ground. The secondary voltage of a potential transformer is designed for about 110 volts, and the secondary current of a series transformer is designed for about 5 amperes. Both of these secondary circuits and the cases of the meters are thoroughly grounded.

The first difference to be noted between current and potential transformers is that the primary of the former is in series with the line and the primary of the latter is in shunt with the line.

The primary current, then, in a series transformer is a quantity determined by the load in the main circuit, the primary e.m.f. being merely the drop in potential across the transformer due to its impedance.

In the potential transformer the primary e.m.f. is that of the main circuit. Fig. 795 shows the connections of instrument transformers and instruments in circuit. Here an alternator supplies a lighting load connected through a power transformer at *L*. The potential transformer *P* causes the voltmeter *V* to indicate the pressure of the line, and the current transformer *C* indicates, on the ammeter *A*, the current in the main line. The current in the series transformer *C* is determined solely by the line current. The pressure on the transformer *P* is determined solely by the line potential. Thus the secondaries of these two instruments will give indications on *A* and *V* which show line current and line voltage respectively.

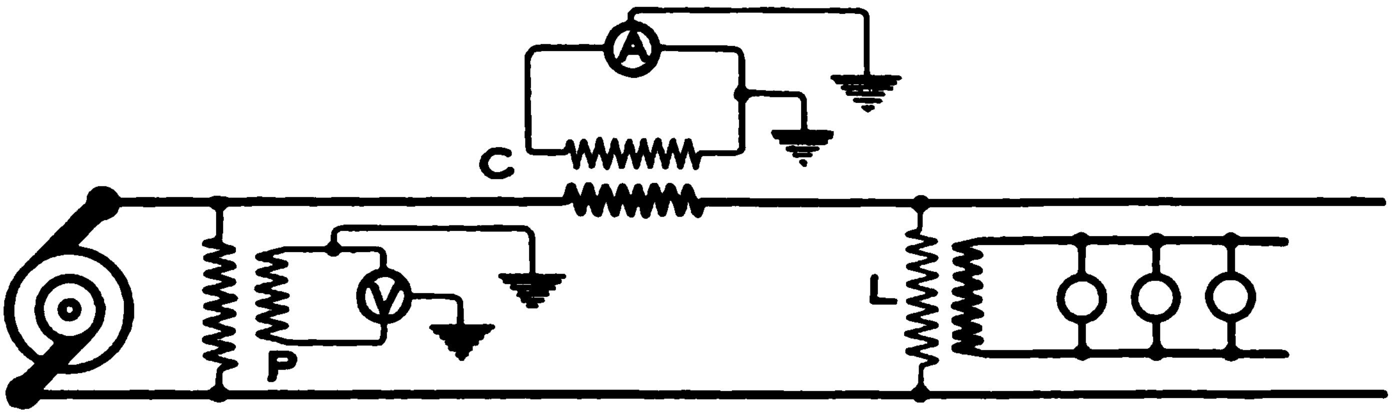


FIG. 795.—Connections of instrument transformers.

Series Transformers

Consider the action of a series transformer with its primary in series with the line and its secondary on open circuit. The primary current, which is the line current, will set up a magnetic field which by self-induction will cause a certain drop across the primary winding. The flux which circulates will also cut the secondary and generate therein an e.m.f. the value of which will equal the voltage drop across the primary multiplied by the ratio of secondary to primary turns, the same as in a shunt transformer. When the secondary is open, all the primary current is effective in producing flux—that is, there is no opposing magneto-motive-force as when there is a secondary current. Therefore the iron of the core becomes highly saturated, and the secondary e.m.f. is high. In a certain case, where a transformer

had a ratio of 10 amperes to one-half ampere, the secondary e.m.f. rose to 4,000 volts.

The secondary of a series transformer should never have its winding open circuited while there is current in the primary, for two reasons.

First: A dangerously high voltage may be established which might cause injury, even if it did not prove fatal, should any one come in contact with it.

Second: The high flux resulting from the open circuiting of the secondary would saturate the iron to such a degree as to seriously impair the ratio of the transformer.

Consider the secondary circuit of a series transformer closed through a resistance. The secondary current and magneto-motive-force oppose and reduce the flux and therefore reduce the secondary e.m.f. When the secondary circuit is first closed, the secondary e.m.f. may be 4,000 volts and the current in the secondary circuit zero. The high voltage in the low resistance of the closed circuit immediately commences to produce a current. This current rises and with it the magneto-motive-force of the secondary, which in turn reacts on the flux. As the flux falls the secondary voltage falls. The secondary current continues to increase and the secondary e.m.f. continues to decrease until equilibrium is reached at some particular point where the secondary e.m.f. is just high enough to maintain the secondary current. This adjustment between secondary current and e.m.f. takes place practically instantaneously. The resistance in the secondary circuit is usually low. Therefore the secondary e.m.f. in this closed circuit is low and the flux required to produce it is small.

If no magnetizing current were required, the secondary ampere-turns would exactly balance the primary ampere-turns, and the ratio of transformation as regards the primary amperes to secondary amperes would be the inverse of the ratio of the number of turns. To cause the current to have this ratio as nearly as possible the iron is worked at a very low flux density so that very little magneto-motive-force is required. The flux density in a series transformer is only about one-tenth of that employed in regular power transformers. An ordinary shunt or power transformer would therefore not be suitable to use as a current transformer even if it had the proper ratio.

As the load current increases, the current in the primary of the series transformer also increases. This increases the primary ampere-turns. This will immediately establish a greater difference between the primary ampere-turns and the secondary ampere-turns, which will cause an increase in the flux This increases the induced secondary e m f , which in turn will raise the secondary current. As the secondary current increases it reacts on the magnetic circuit to reduce the flux A stable condition will be reached when the primary current is just able to circulate the slightly increased flux The ratio between the primary and secondary currents will remain practically the same as before the load current increased, because of the negligibly small additional magneto-motive-force required. There is, of course, a slightly greater resultant magneto-motive-force required when the primary current increases on account of the greater secondary e m f required by the greater secondary current.

Fig 796.

A change in resistance of the secondary circuit is the cause of a similar change in conditions. When the secondary resistance is increased the secondary current momentarily decreases and the flux increases. Then the secondary e m f. increases, and likewise the secondary current. When equilibrium is finally reached there is a greater secondary e.m.f. and a very slightly less secondary current. Thus two ammeters may be put in series on the secondary of a series transformer, and the indications of each would be practically the same as though but one were connected in circuit, for an increase in secondary resistance does not by any means bring about a proportionate decrease in secondary current, as would be the case with a shunt transformer. It merely means that the secondary current will decrease by the amount necessary to permit a sufficient increase in the flux and therefore in the secondary e m f. to circulate the current through the increased resistance.

The fact that the current ratio is not appreciably affected by the changes within certain limits of the secondary resistance and primary current is due to two reasons.

First: The magnetization is very small

Second: The magnetizing current is not in phase with either the primary current or the secondary current, but is out of phase with each by nearly 90° Thus in Fig. 796, *O-M* repre-

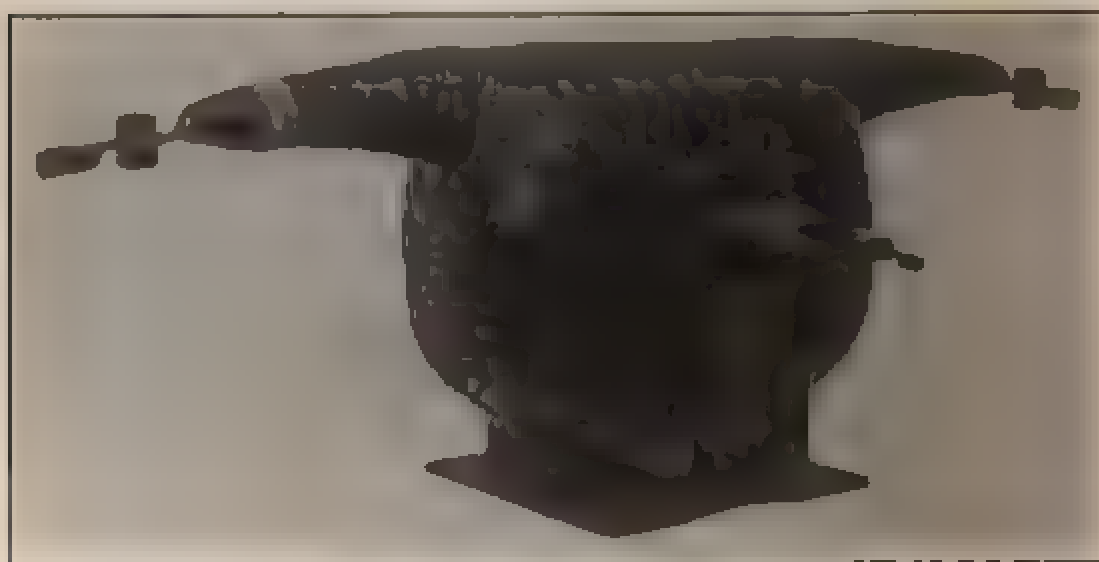


FIG. 797 Actual appearance of General Electric current transformer.

sents the magnetizing current, *O-P* the primary current and *O-S* the secondary current.

Fig. 797 shows the general appearance of a General Electric current transformer insulated for a 15,000-volt circuit and having a capacity of 100 amperes in primary and 20 amperes in

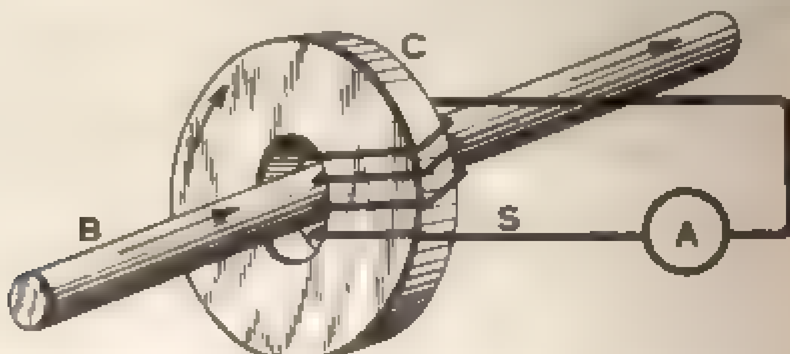


FIG. 798. -Theoretical arrangement of current transformer.

secondary Current transformers of large capacity, however, often have a very different appearance Thus the primary may consist of nothing but one of the main cables or bus bars such as *B* Fig 798 passing through a laminated iron ring *C* which surrounds it Wound on this ring are the secondary turns *S*, which lead to the ammeter *A*. The primary winding here

consists of a straight conductor really not more than one-fourth of a turn but, if carrying 100 amperes, having the effect of approximately 25 ampere-turns

Potential Transformers

Fig 799 shows the general appearance of a General Electric potential transformer for operating instruments and relays.

FIG. 799. Actual appearance of General Electric potential transformer for operation of voltmeters and relays.

The primary is wound for 13,200 volts, and the instrument side for 110 volts.

The protecting fuses and barrier between the high potential terminals are shown at the top.

Connection of Instrument Transformers

There are five principal methods of grouping the secondaries of series transformers on three-phase circuits for operating the various instruments and protective devices.

First: The **reversed V.** This connection is illustrated in Fig. 800 and is the one commonly used for the operation of indicating meters.

Second: The **open Δ** or **V.** This connection is shown in Fig.

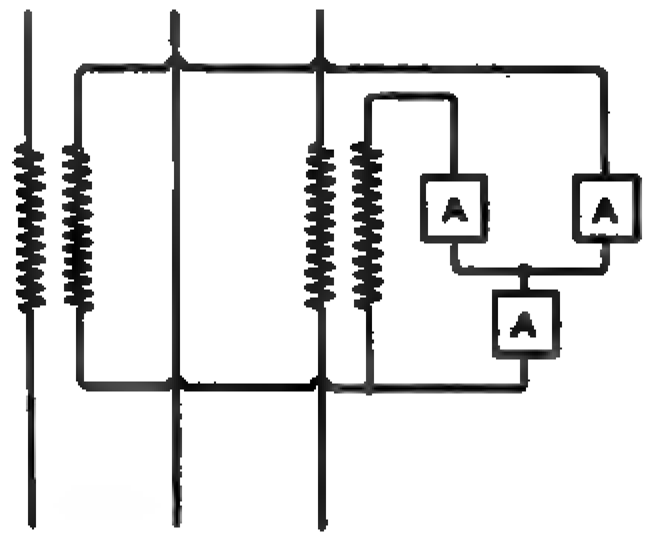


FIG. 800.—Reversed V connections of instrument transformers.

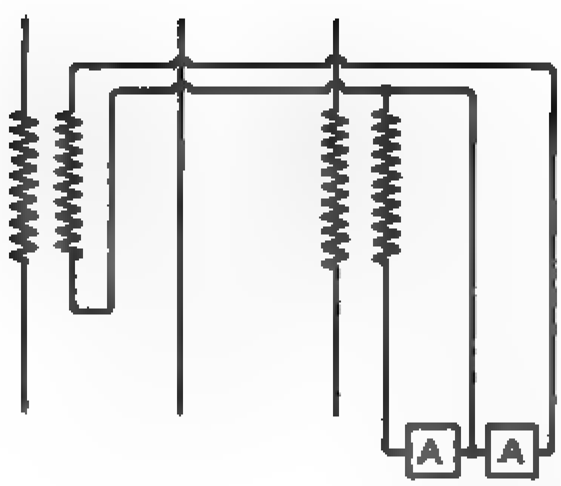


FIG. 801.—Open-Δ or V connection of instrument transformers.

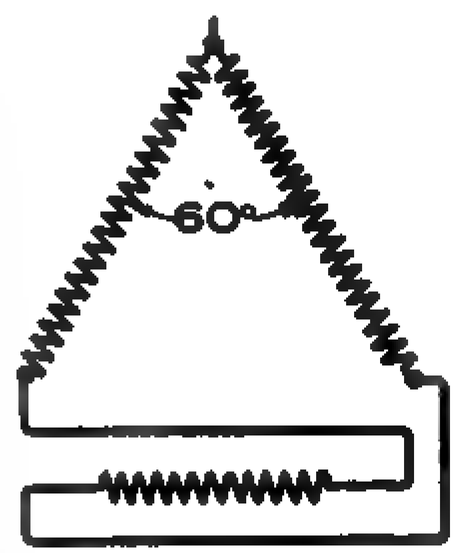


FIG. 802.—Z connection of instrument transformers.

801 and is the most suitable for operation of voltage compensators and voltage regulators

Third: The Δ connection.

Fourth: The **Z** connection. This connection is the same as the Δ except that one of the secondaries is reversed with respect to the other two as in Fig. 802. The Z connection is the one preferred in order to obtain the best protection for three-phase

circuits with overload relays. The connections are shown in Fig. 803.

Fifth: The **Y** connection, shown in Fig. 804.

Fig. 805 shows the various instruments which may be operated from current and potential transformers on a three-phase system.

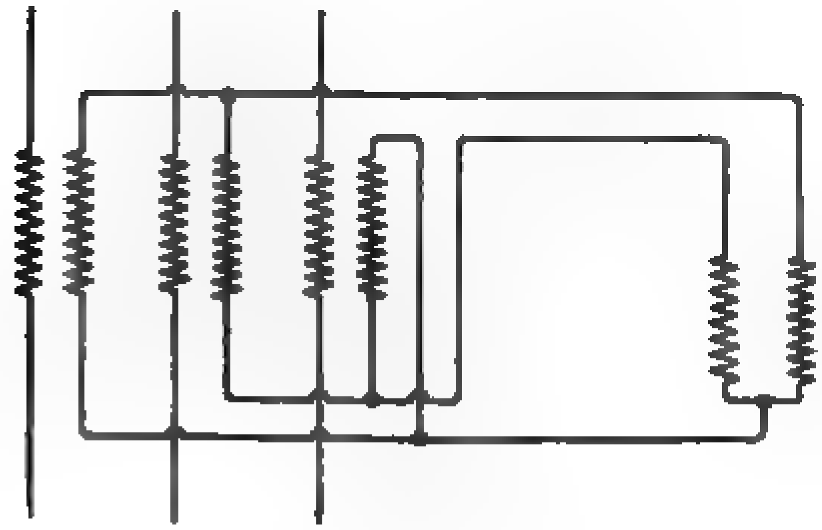


FIG. 803.—Theoretical circuits of three transformers connected in Z.

While not representing the arrangement followed in actual practice, it gives a general idea of the positions of the instruments and transformers necessary to operate them. A three-phase circuit with lines 1, 2 and 3 supply power to a load situated at *A-B-C*. Two potential transformers *D* and *E* with their

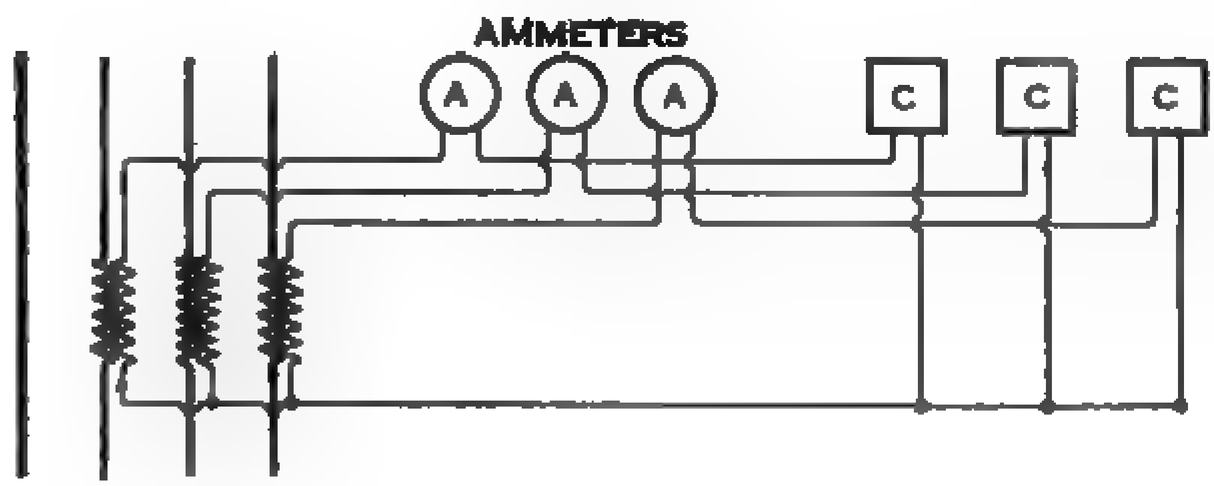


FIG. 804.—Y connection of current transformers.

primaries connected, one across each of two phases, supply the potential circuits of the indicating wattmeter *W*, the recording wattmeter *WH*, the two potential circuits of the power factor meter *PF*, and the voltmeter *V*.

The two current transformers *G-H* have their primaries in two

of the three phases while their secondaries are connected in reversed V, supplying three ammeters, A, A' and A'', the current circuits for two phases in the indicating and recording wattmeters W and WH, the R, R', energizing coils responsive to the line current in the relays R, R', the current coils of power

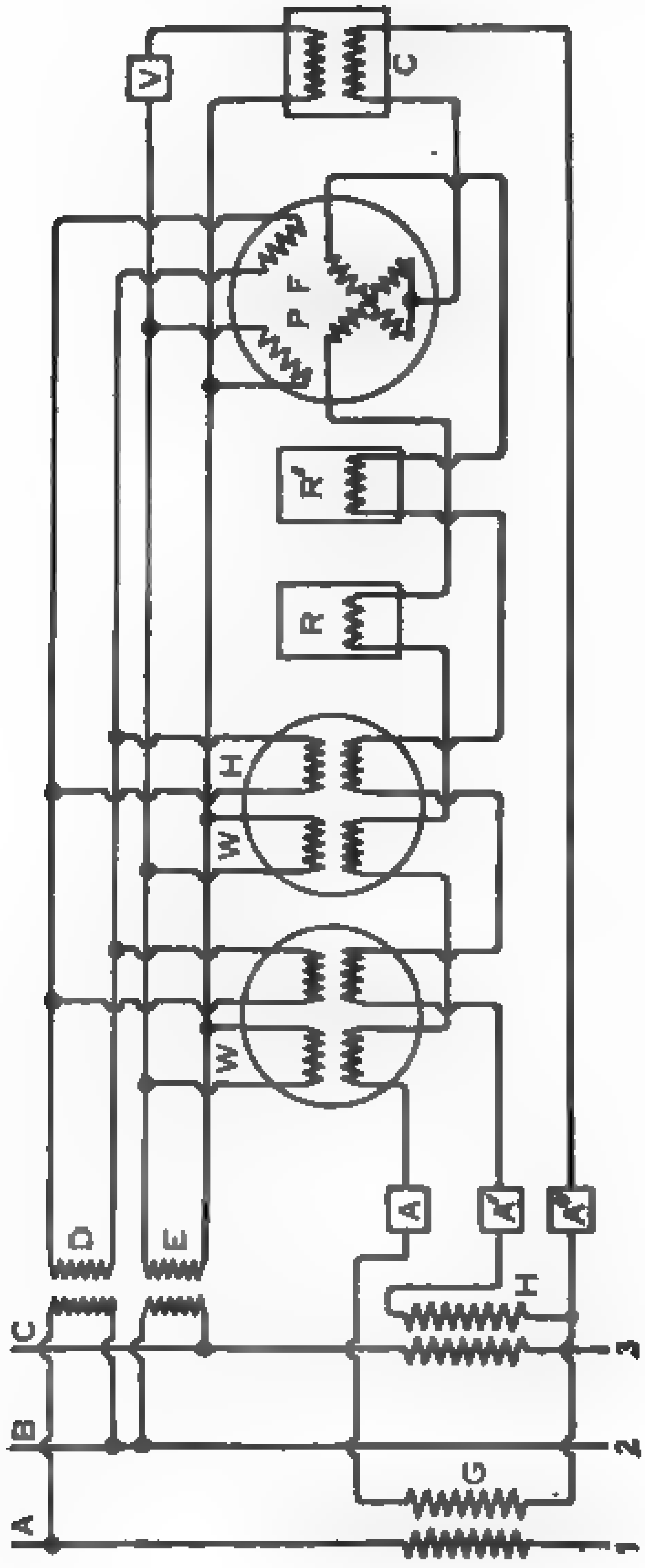


FIG. 805.—General arrangement of current and potential transformers for supplying relays, indicating and recording instruments on a three-phase system.

factor meter *PF*, and the series coils of the compensating device *C* which lowers the indications of the voltmeter *V* in proportion to the load on the line, thus enabling the voltmeter to show the voltage at the load instead of the voltage at the station. The current in the ammeter A'' is the geometric sum of the currents in the meters *A* and A' and consequently indicates the current in the line wire 2, provided, of course, the load is balanced. This line 2, however, does not pass through any transformer. Ordinarily the two series transformers *G-H* would not be sufficient to operate accurately so many series instruments. Another pair of series transformers would probably be required, their primaries would be connected in series with the lines 1-3 and the meters divided between the secondaries of the two sets of transformers.

SECTION XV CHAPTER IX

TRANSFORMERS

INSTRUMENT TRANSFORMERS

1. What is meant by the term "Instrument Transformer?" For what and why are they used?

2. (*a*) Can a power transformer be used for voltmeter work?
   (*b*) Wherein do potential transformers differ from them?

3. (*a*) Explain briefly the construction and operation of a current transformer.
   (*b*) Why should the secondary winding never be open-circuited?

4. Sketch line connections for the following arrangements of instrument transformers: Reversed V; Open Δ; and Z. For what class of work is each best adapted?

5. What is the effect of resistance in the secondary circuit of a current transformer upon the current ratio and the phase relation of current and potential? Why is this so?

6. What is the effect upon the ratio of currents and phase relation of current and voltage in a current transformer, if reactance be added to the secondary circuit? Why is this so?

A. C. MOTORS

SYNCHRONOUS MOTORS

Broadly there are two classes of alternating-current motors; the synchronous and the non-synchronous groups. The first includes motors running the same number of revolutions as the alternator supplying them, or, more accurately, at the same speed pole for pole. The other group includes a variety of alternating-current motors such as the induction motors and other types, most of which run at something less than syn-

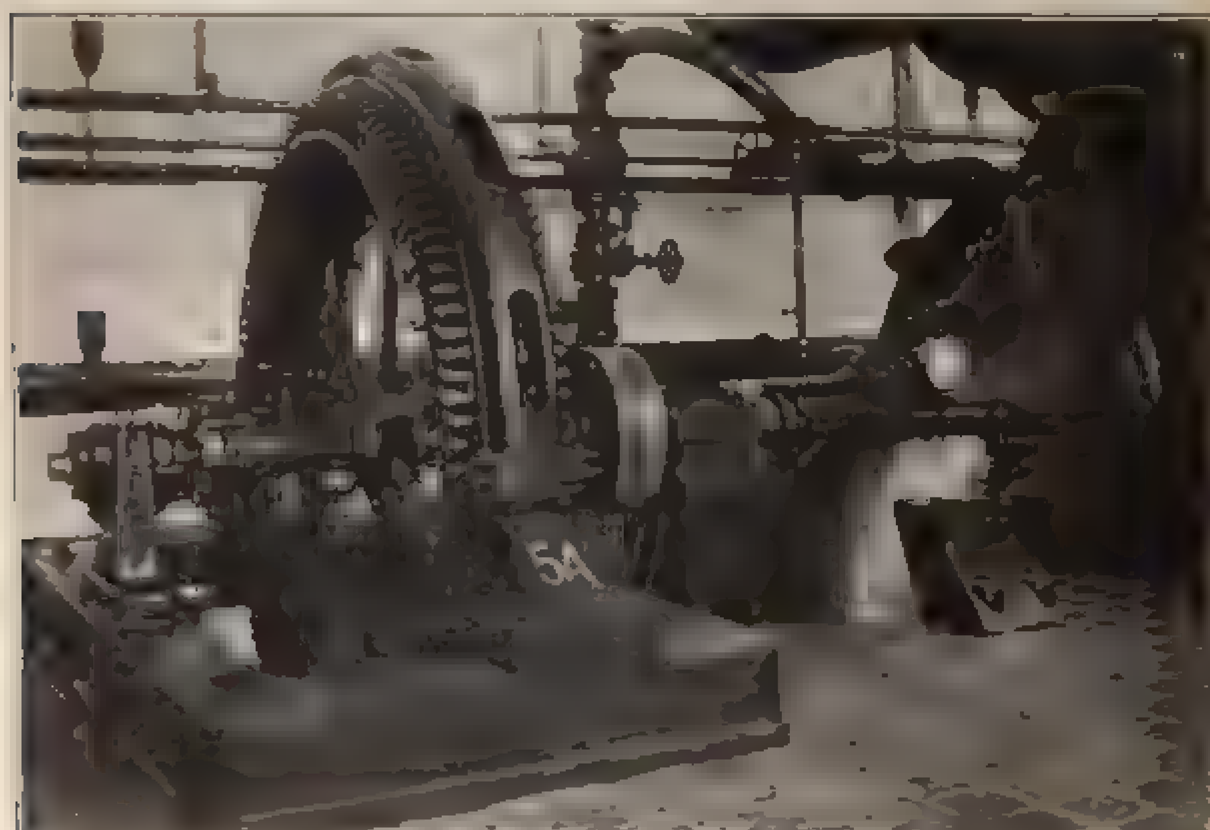


FIG. 805 A.—Westinghouse, 450 horse power, synchronous motor, 2,300-volts, 105 r.p.m., 100 % power factor, driving Southwark pump.

chronous speed, while a few occasionally run at or slightly above synchronism.

The synchronous motor is a duplicate of the synchronous generator. It usually consists of a revolving field structure and a stationary armature with a distributed winding and is supplied with direct current through brushes and slip rings from a separate direct-current exciter.

An illustration of the practical application of the synchronous motor is given in Fig. 805-A which shows a Westinghouse 450-horse power, 2,300-volt, three-phase, 60-cycle, machine of this type, operating at 100% power factor, driving a Southwark pump 105 r.p.m. in the city of Portland, Oregon.

The armature of a direct-current motor revolves through the reaction between the current in a moving wire and a stationary magnetic field. In the generator the inherently alternating current is led through a commutator to the external circuit, thence through a transmission line to the commutator of a direct current motor. In the motor this current again alternates. As these alternations are similar the question naturally arises: Why have a commutator on the motor to undo the work of the commutator on the generator? As the current is to alternate in both machines, why can it not be permitted to alternate in the line? The answer may very readily be found. The current in the generator alternates with a frequency determined by the speed of the prime mover which drives it. The current in the motor alternates with a frequency depending upon the motor's speed. The greater the load the slower the motor will run and the slower the frequency of the current in this armature.

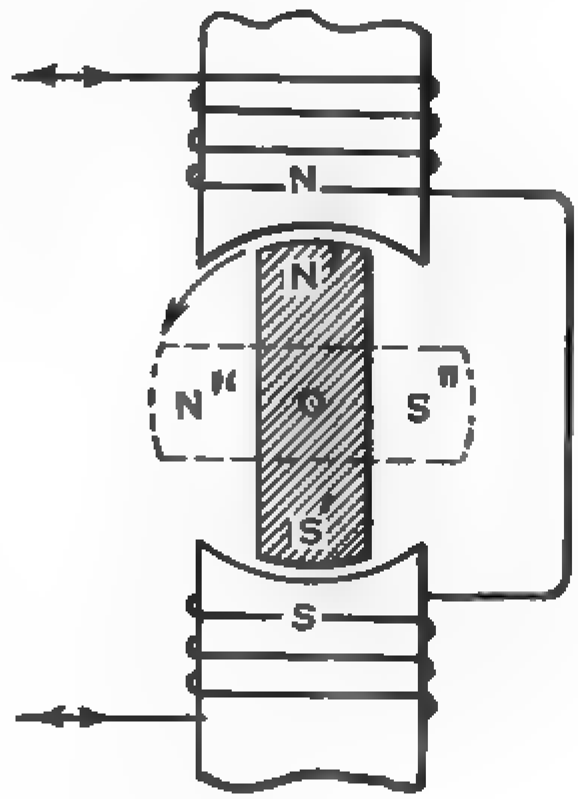


Fig. 806.—Principle of synchronous motor.

In order that both the commutators may be abolished, it will be necessary for the armature of the motor to run in exact synchronism with the armature of the generator so that the arrival of the current in the motor's armature will be properly timed to suit the particular position of the armature poles at a given instant with respect to the field poles. Any variation in speed of the motor with respect to the generator would therefore throw the two out of step and the motor would shut down.

In Fig. 806 let an alternating current be delivered through

the lead wires to the stationary armature of a synchronous motor so that at a given instant the polarity produced by the initial current will be N-S as shown. Consider a permanent magnet pivoted between these poles in the position shown in full in N'-S'. The polarity established by the alternating current would repel the two poles of this field magnet, but they would simply exert a direct repulsion which, with respect to the pivoted point, would admit of no motion. Even should the magnet be turned into the position N''-S'', the situation would not be improved, for the poles N-S would first repel the poles N''-S'', and with a 60-cycle circuit, $1/120$ of a second later, the main poles N-S would change to S-N. These would attract the poles N''-S'' so that

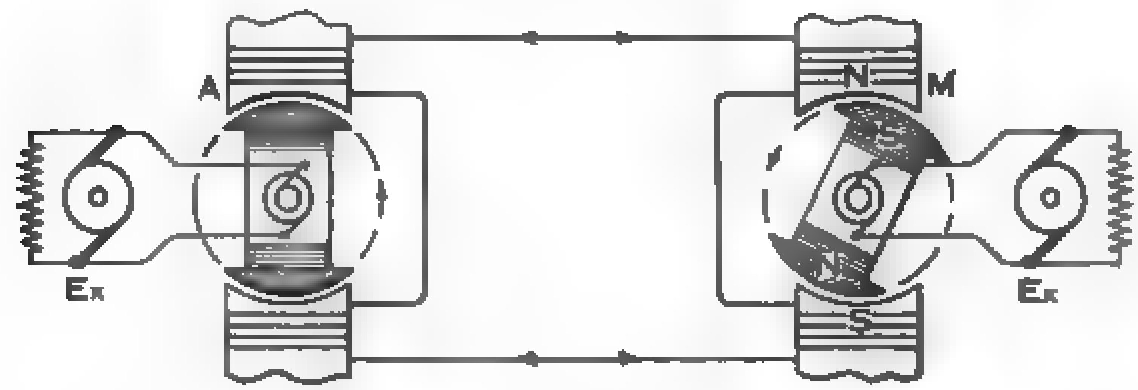


FIG. 807.—General scheme of alternator and synchronous motor with separate exciters.

every $1/120$ of a second there would be first a repulsion and then an attraction between a given armature pole and a certain field pole and the inertia of the revolving mass would prevent the field structure from moving at all. If, however, the frequency of the source of supply were reduced or if the revolving member were given an initial impulse so as to rotate it to the position shown in full in the figure, reaching this position at the exact instant when the polarity of the armature was rising, the momentum of the field member would carry it past dead center and repulsion would ensue between N and N', and S and S', and the field structure would continue to revolve in the direction of the arrow. If the initial impulse were sufficient to carry the field a half-revolution during one alternation so that the pole N' reached the armature pole S and the field pole S' reached the armature pole N, just as the armature polarity changed to S-N, then each pole of the field would receive an added impulse of repulsion from one armature pole and attraction from the other

armature pole, and the rotation would continue in the direction in which the rotor was originally started. This rotation could only be kept up provided the field structure performed a half-revolution for every alternation of the armature current.

Fig. 807 shows the complete circuits for an alternator and synchronous motor. Each machine is provided with its own exciter, and the revolving fields receive direct current through

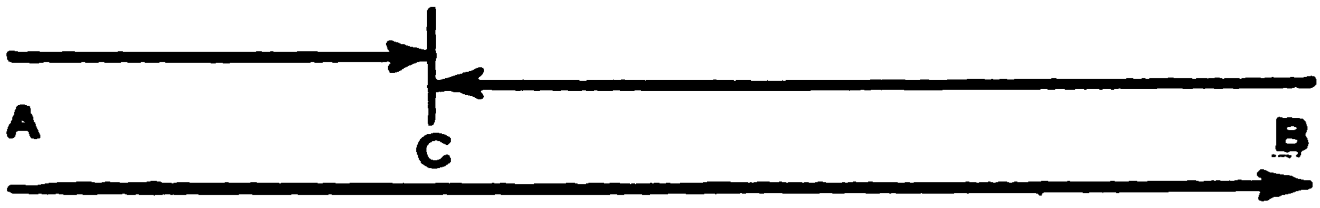


FIG. 808.—Relation of e.m.fs. in a direct current motor.

slip rings and brushes. The current emanating from the alternator, *A*, passes through the connecting line to the stationary armature of the motor. At a given instant the polarity of the motor armature is *N-S* as shown, while the polarity of the field is *S-N*. The inertia of the motor's field structure is too great to allow it to move but, if once started and brought up to synchronous speed, it will continue to run in the direction in which it is started. Such a motor runs equally well in either direction.

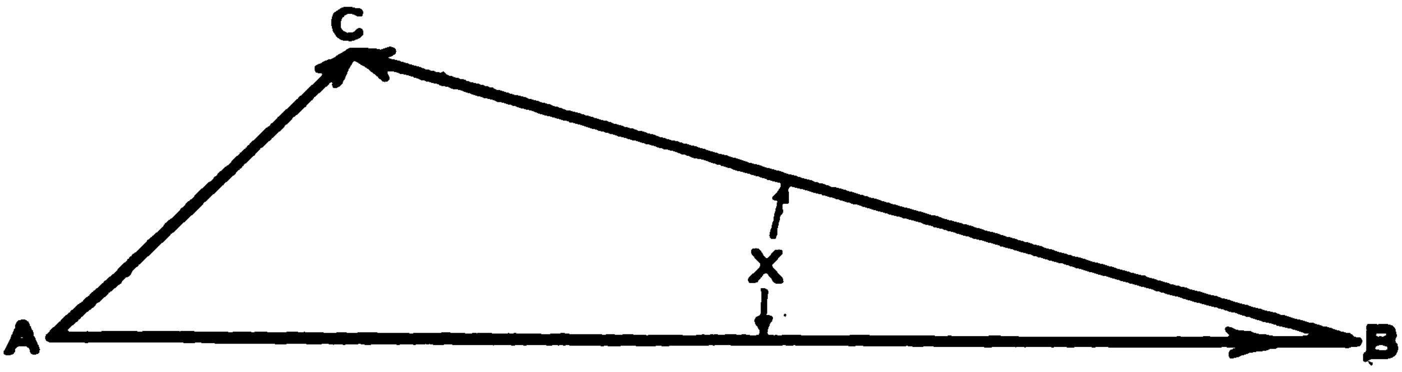


FIG. 809.—Relation of e.m.fs. in alternating current synchronous motor.

If a synchronous motor must run at absolutely the same speed pole for pole as the generator which supplies it, the question naturally arises: How can it get the necessary current under changes in load, if its speed, and therefore the magnitude of its counter e.m.f., cannot alter?

The relation of the various voltages to one another in a direct-current motor are shown in Fig. 808, where *A-B* is the impressed e.m.f., *B-C* the counter e.m.f., and *A-C* the effective e.m.f. In a synchronous motor the relation of the various voltages is shown in Fig. 809. Here, as before, *A-B* is the impressed e.m.f.,

but the counter e.m.f. *B-C* is not diametrically opposed to the impressed but varies therefrom by a certain angle *X* depending on the load. The effective e.m.f. as before is *A-C*, but in this case it is the geometric difference between the counter and impressed e.m.f. instead of the arithmetical difference as in a direct-current motor.

The effect of varying loads in a synchronous motor may be understood from an analysis of Fig. 810. This analysis will be

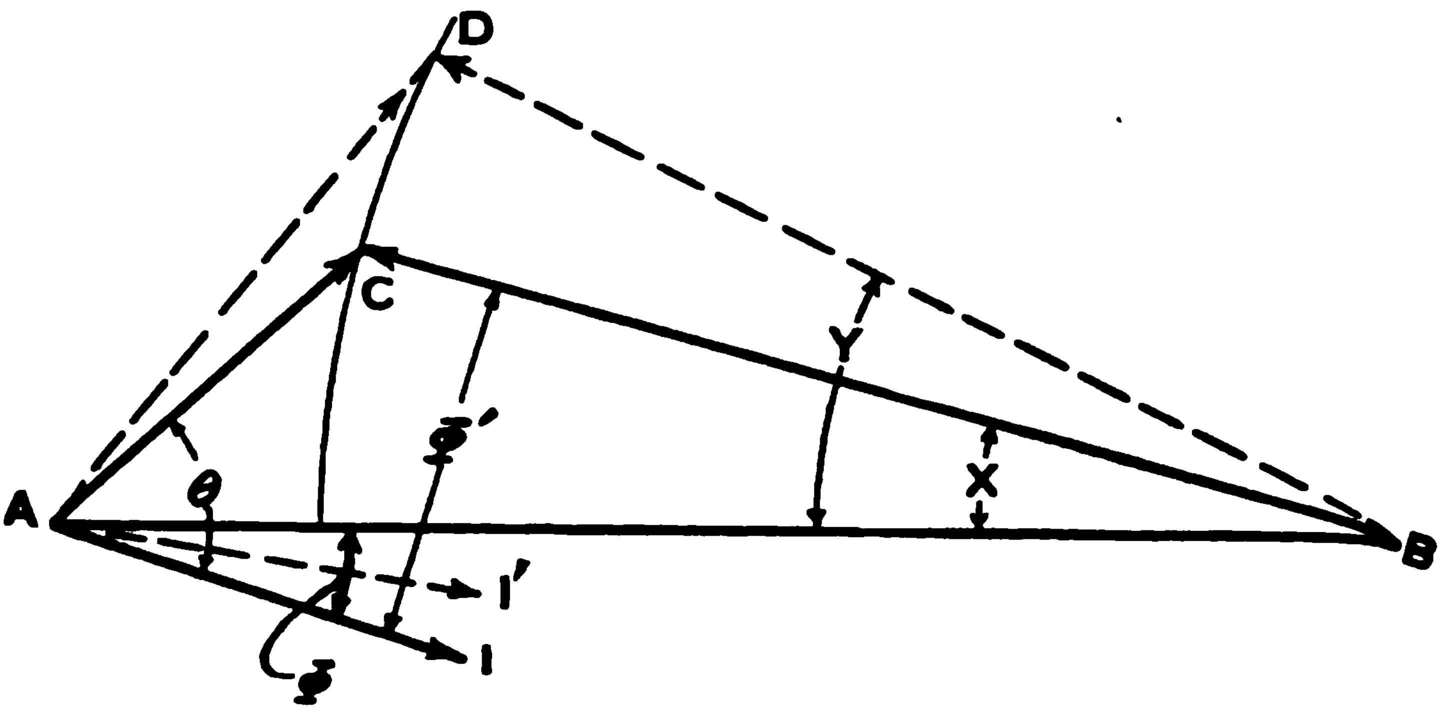


FIG. 810.—Change in phase angle of counter e.m.f. in synchronous motor under variations in load.

based on the assumption that the armature reaction and reactance may be considered as equivalent to a constant armature reactance. Suppose the armature of the motor in Fig. 807 possesses 5 ohms resistance and 10 ohms synchronous reactance. The impedance will obviously be

$$Z = \sqrt{R^2 + X^2} = \sqrt{5^2 + 10^2} = 11.18 \text{ ohms},$$

Fig. 811. The angle θ will be the angle between the current which will be in phase with the energy component of *A-B* and the effective e.m.f., *A-C*, which overcomes the armature impedance.

Now let *A-B*, Fig. 810, represent 1,000 volts impressed on the armature, while *B-C* represents 800 volts counter e.m.f. This counter e.m.f. bears the phase relation of *B-C* with respect to *A-B*, because under the particular load at which the motor is operating the armature must sag back, thereby changing the angle of the counter e.m.f. from direct opposition to the position *B-C*. This angle *X* may be called the angle of sag. The effective e.m.f. will therefore be *A-C*, which is about 300 volts in

this particular case. The current which the armature will receive will be

$$\frac{E}{Z} = I = \frac{300}{11.18} = 26.8 \text{ amperes.}$$

This current will have the direction A-I displaced from A-C through the angle θ, established by the impedance of the armature. The input to the armature will be $E \times I \times \cos \Phi$, where E is the impressed voltage, I the armature current, and Φ the angle between them. The power utilized by the armature which measures the output will be $E' \times I \times \cos \Phi'$ where E' is the counter e.m.f. and Φ' is the angle between the counter e.m.f. and the current.

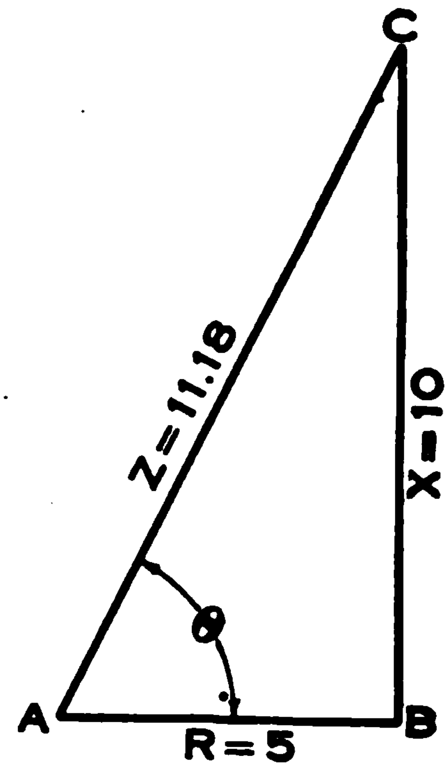


FIG. 811.—Impedance triangle for motor armature.

Now consider what happens when the load upon the motor is increased. The first effect is for the rotor to react, thus sagging back through a greater angle Y. The counter e.m.f. swings to the position B-D. It has not altered in magnitude, but it is changed in phase angle, resulting in increasing the effective e.m.f. from A-C to A-D, which now becomes about 425 volts. As

$$\frac{E}{Z} = I = \frac{425}{11.18} = 40.25 \text{ amperes}$$

and the phase angle of the current swings from A-I to A-I', still preserving the same angle θ between the effective e.m.f. and the current. An increase in the load thus results in an improved power factor, for the angle B-A-I' is less than B-A-I. If the load increased still further, the angle B-A-I would evidently grow less and less until A-D-B became a right angle. In the case shown, the angle at that time between the impressed e.m.f. and the current would be very small and the power factor almost 100%. For a given excitation there will then be a particular load at which the power factor is a maximum.

It has been assumed that the impedance of the armature would be the same under all conditions. As a matter of fact it changes slightly.

Next consider what will happen if the excitation of the motor is varied. The counter e.m.f. of a direct-current motor was the

product of its flux, speed and conductors. The same is equally true for a synchronous motor. In a shunt motor the speed varied under changes in load, while the flux and conductors remained constant. In the synchronous motor the speed cannot change. The number of conductors remains constant, but the flux may be varied by inserting resistance between the exciter and the motor's field. In a direct-current motor the counter e.m.f. cannot exceed the impressed. In a synchronous motor the impressed e.m.f. reaches zero 120 times a second with a 60-cycle supply, and there is nothing to hinder the counter e.m.f. at such a time greatly exceeding the impressed. As the conductors and speed are constant, the counter e.m.f. may be governed solely by the extent of the field excitation. Take the same example; *O-B*, Fig. 812, represents 1,000 volts impressed on the

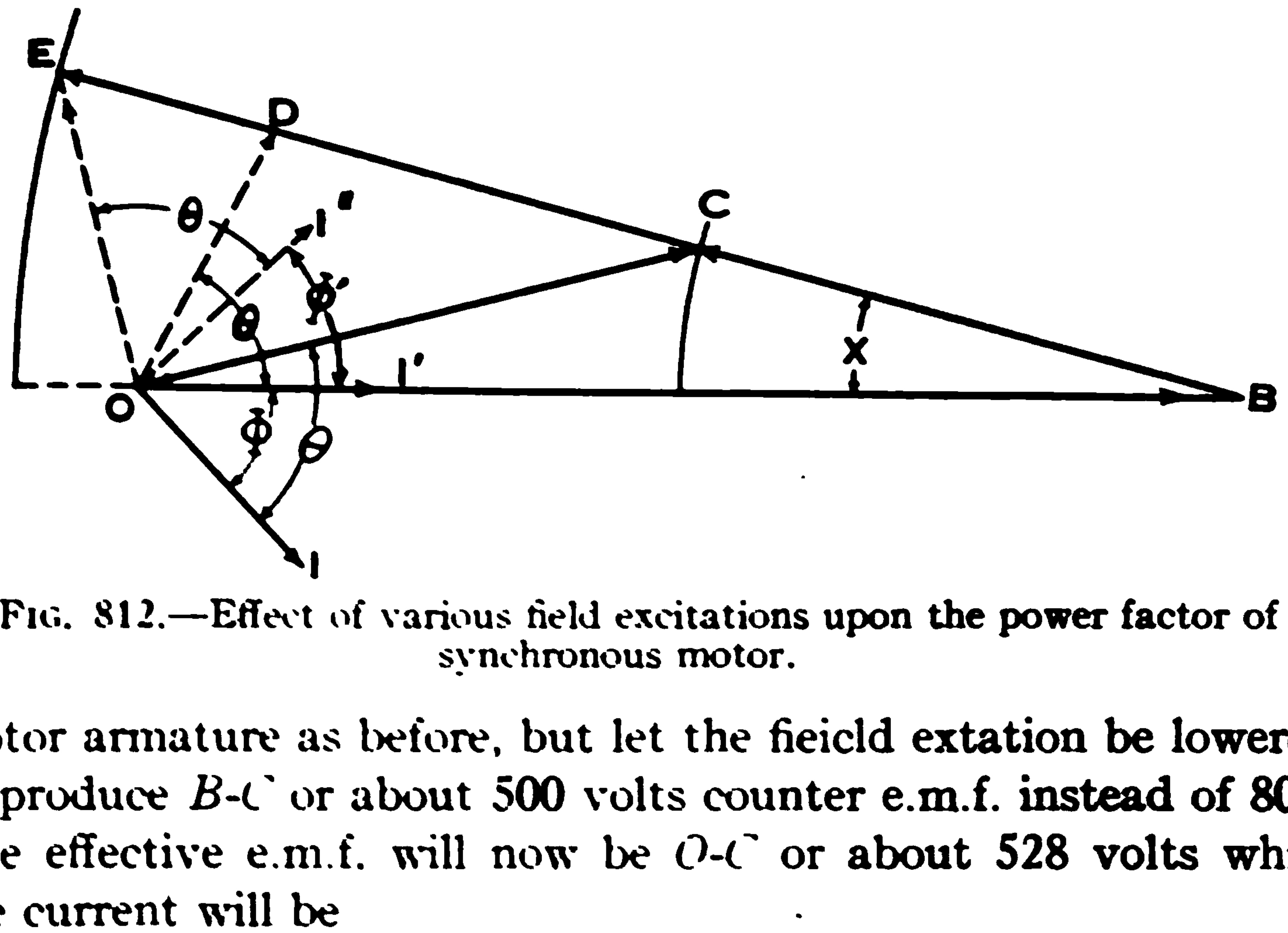


FIG. 812.—Effect of various field excitations upon the power factor of synchronous motor.

motor armature as before, but let the fieicld extation be lowered to produce *B-C* or about 500 volts counter e.m.f. instead of 800. The effective e.m.f. will now be *O-C* or about 528 volts while the current will be

$$\frac{E}{Z} = I = \frac{528}{11.18} = 47 \text{ amperes.}$$

This current will have the direction *O-I* and the angle of lag Φ between the impressed e.m.f., and the current will be much greater than before. Thus a lowering of the field excitation is accompanied by an increase in the armature's ampere intake and a lowering of the power factor.

Next let the field excitation be greatly increased until it equals *B-E*, or 1,100 volts. The effective e.m.f. will now be *O-E* and

the current will swing around into the position O-I'', always bearing the same angular relation θ to the effective e.m.f. Now, instead of an angle of lag, Φ, there will be an angle of lead, Φ', and the current will be approximately 25 amperes. If with under excitation the current lags and with over excitation the current leads, it must be evident that with some particular excitation such as B-D corresponding to about 910 volts, the effective e.m.f. being O-D, the current O-I'' would swing back into the position O-I', where it would be exactly in phase with the impressed e.m.f. O-B, thus giving a power factor of 100%. It must be understood that this variation of field excitation has been brought about by manipulation of the field rheostat and without any change in load whatever. The current intake for a given load with either overexcitation or underexcitation would be greater than when the current was in phase with the impressed

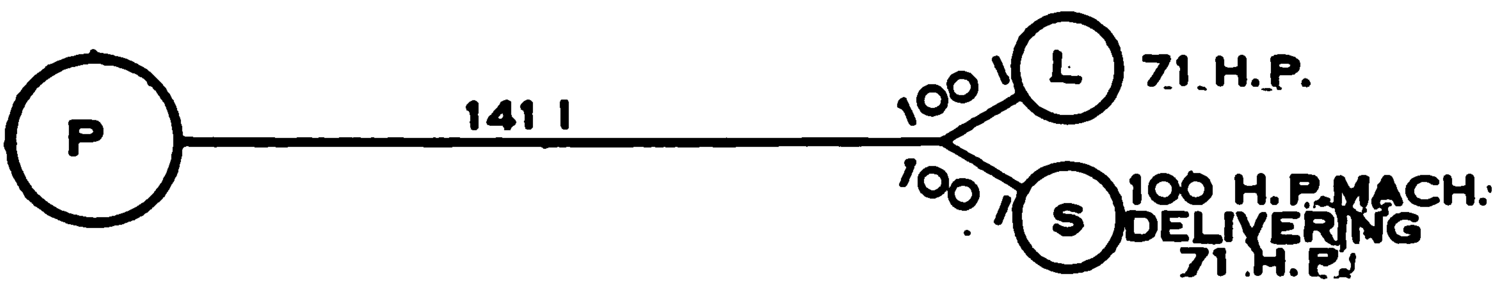


FIG. 813.

e.m.f.; thus the rheostat could be varied until for a given load the current intake was a minimum. This would then indicate a power factor of 100%.

It should be understood, however, that the field flux in a synchronous motor does not vary through as wide a range as might be assumed from the vector diagrams. Any change in the field current tending to raise or lower the actual flux across the windings is accompanied by a change in the value and phase relation of the current in the armature, which tends, through armature reaction, to maintain the field flux constant. Unfortunately it is not possible to treat of these two conditions simultaneously with a single vector, it being necessary to consider the motor either as having no armature reaction or as having no armature reactance. As similar conclusions are reached in either case, this fact is no objection to the treatment of the subject.

A synchronous motor will take more current to deliver a given amount of power at its pulley with its field overexcited or underexcited than it will when its field is excited to the proper

amount to bring the line current and e.m.f. into phase with each other. Thus if a certain motor required 100 amperes at 100% power factor to deliver 100 horse power, by weakening the field excitation a certain amount or strengthening the field by a certain amount the motor could be made to absorb 125 amperes instead of 100 while delivering the same power at its pulley.

If a synchronous motor is to be used in its capacity as a condenser for improving the power factor, the armature must be capable of carrying the extra current above referred to, or the load upon its pulley must be reduced. In other words, there must be a certain margin between the real energy and the appar-

FIG. 814.

ent energy in the design of the machine, and this margin represents the available wattless component of leading current which may be obtained for neutralizing a corresponding component of lagging current in the system. Let a generating plant P, Fig. 813, supply power over a transmission line to an induction motor load L, of 71 horse power. Let this motor require 100 amperes at 71% lagging power factor. At a nearby point is a synchronous motor load S, consisting of a 100 horse power machine which by means of an over excited field is made to absorb 100 amperes and deliver 71 apparent horse power wattless leading current and at the same time 71 horse power energy from its pulley. The **wattless leading** current of S will neutralize the **wattless lagging** current of L so that, instead of the transmission line being obliged to carry 200 amperes, it only carries 141 amperes, and the wattless lagging current of L and the wattless leading current of S oscillate between these two motors, while the transmission line carries no wattless current at all. Thus, if in Fig. 814 the load at L of a given horse power had a 71% power factor lagging, then an equal load at S involving a 71% power factor leading current would produce a 100% power factor in the transmission line.

The most advantageous way to use a synchronous motor is in its combined capacity as a source of mechanical energy at its

pulley and leading current to the line. Thus, if a machine has a total apparent capacity of 100 kilowatts, Fig. 815, it can deliver 71 kilowatts of real energy at its pulley and at the same time

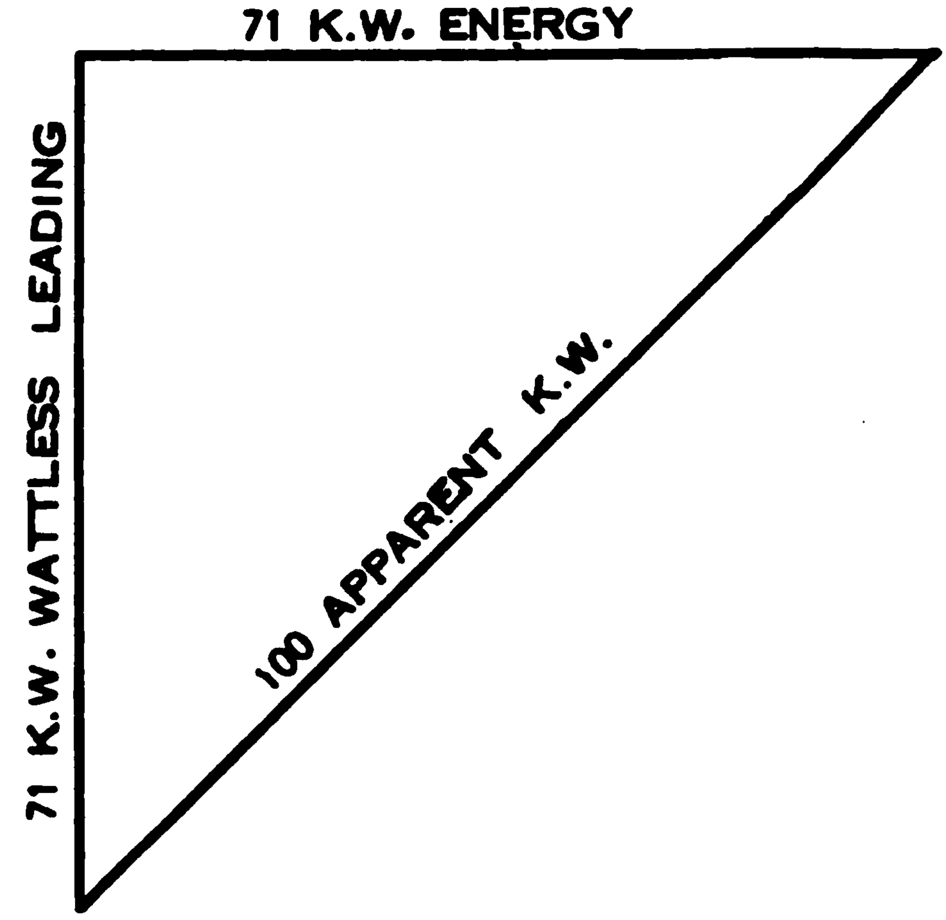


FIG. 815.

deliver 71 kilowatts of wattless leading current to the line which will neutralize 71 kilowatts of wattless lagging current anywhere else in the system. The motor would then operate at

$$\frac{\text{Energy kilowatts}}{\text{Apparent kilowatts}} = \frac{71}{100} = 71\% \text{ power factor, leading.}$$

Consider an induction motor load in a system requiring 1,414 apparent kilowatts, *B-C*, Fig. 816, of which 1,000 kilowatts is real energy, the power factor being

$$\frac{\text{Energy kilowatts}}{\text{Apparent kilowatts}} = \frac{1000}{1414} = 71\% \text{ lagging.}$$

Now let synchronous apparatus be added capable of furnishing 500 kilowatts wattless leading current. This would be reckoned downward from *C* to *D* and reduce the apparent input for the combined loads from *B-C* to *B-D*, or 1,120 apparent kilowatts. The saving affected would thus be 1,414 — 1,120 = 294 apparent kilowatts. The power factor would be raised thus:

$$\frac{\text{Energy kilowatts}}{\text{Apparent kilowatts}} = \frac{1000}{1120} = 89\%.$$

Now let more synchronous apparatus be added to the system capable of supplying 500 additional kilowatts wattless leading current. This would be reckoned downward from D to A and would reduce the apparent energy from B-D to B-A, the apparent kilowatts now being the same as the real energy. The saving effected by the addition of the second 500 kilowatts leading current is 1,120 — 1,000 = 120, and the power factor would be raised to 100%.

The introduction of the first 500 kilowatts of leading current to the system effected a saving of 294 apparent kilowatts, while the introduction of the second 500 kilowatts wattless leading

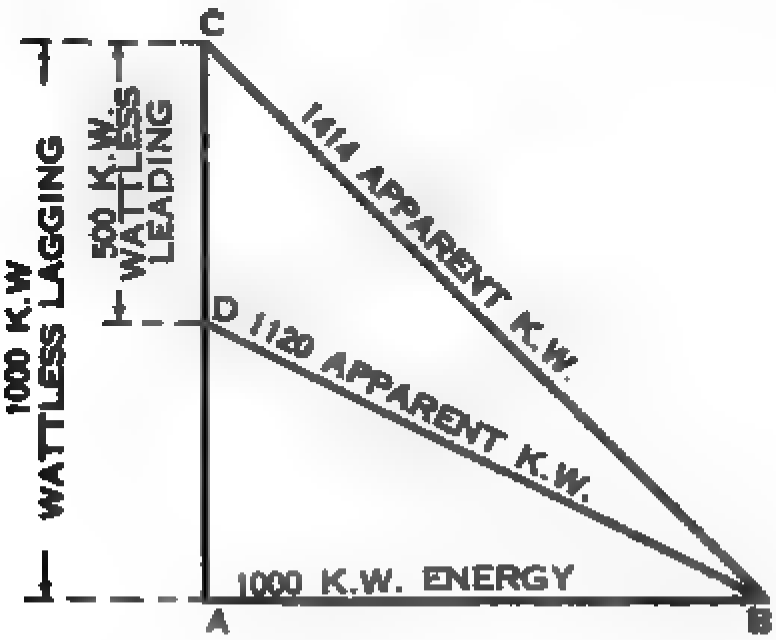


FIG. 816.

current to the system effected a saving of only 120 apparent kilowatts. The conclusion would naturally be that the **rotary condenser saves a larger amount of apparent kilowatts at low-power factor than it does at high-power factor.** Thus the poorer the power factor to begin with the more advantage would be derived from the introduction of the rotary condenser.

In using a synchronous machine as a condenser, the field current must be increased to produce a leading current in the line. The machine must thus be designed to carry this additional field current without overheating the winding and usually involves a special design if the machine is to be worked to its full capacity as a condenser. Thus the limit to the use of an alternator as a synchronous condenser is often reached by the temperature of the field, especially if it is carrying a load on the pulley also.

Fig 817 represents a 250-horse power, 2,200-volt synchronous motor manufactured by the General Electric Company. Note the slip rings for supplying direct current for exciting the revolving field, also the field coils and poles of this structure, and the overhanging protection for the stationary armature.

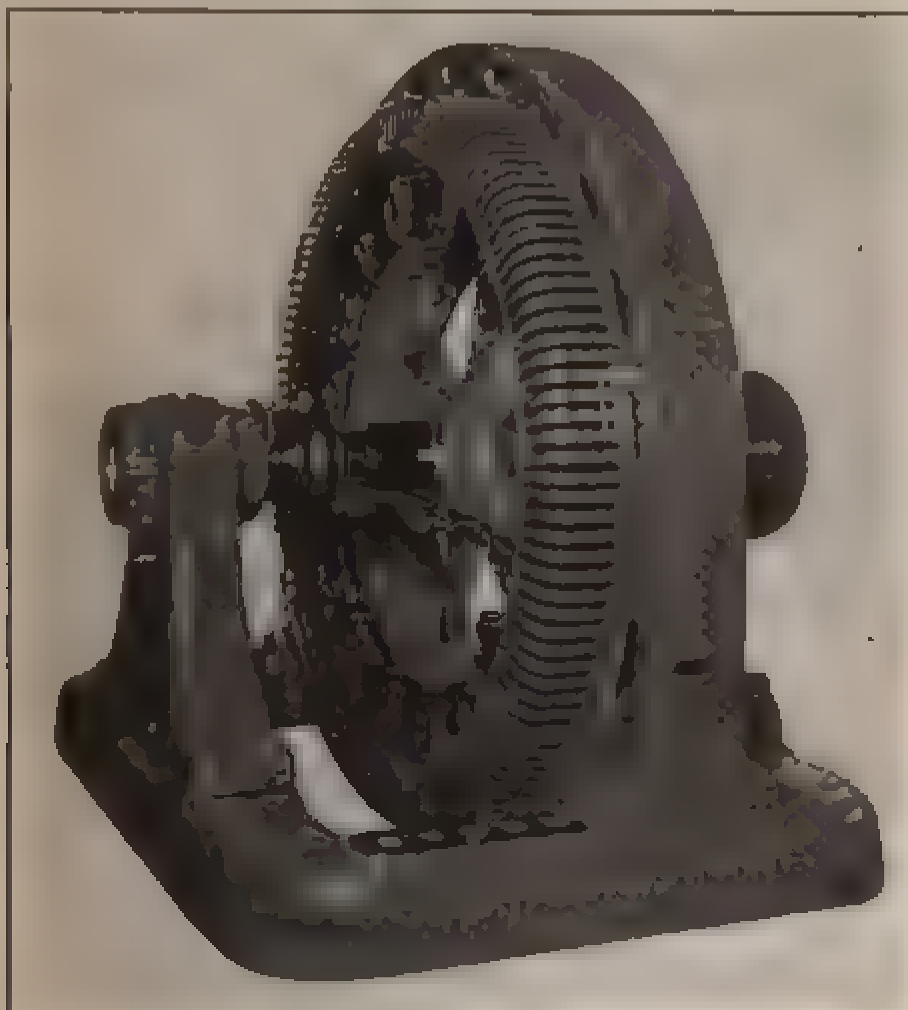


Fig. 817.—250 horse power 2,200-volt synchronous motor manufactured by The General Electric Company.

SECTION XVI CHAPTER I

ALTERNATING-CURRENT MOTORS

SYNCHRONOUS MOTORS

1. Give a diagrammatical sketch of a synchronous motor. Explain its construction and principle of operation.
2. What are the various methods of starting a synchronous motor?
3. How does a synchronous motor get the necessary current under variations in load if its speed does not alter?
4. For a given load, what is the effect upon the line current both as to amount and phase relation with respect to the impressed e.m.f. when the field excitation of a synchronous motor is altered?
5. What is the effect of a synchronous motor load operating with over-excited field upon the power factor of a system already carrying an induction motor load?
6. Does the addition of a given amount of synchronous motor load prove most useful upon systems having a very bad or a moderately good power factor? Explain fully why.

A. C. MOTORS

THE ROTARY MAGNETIC FIELD OF FORCE

The rotary magnetic field of force exists in both synchronous and induction polyphase motors. The discovery of the principles of this rotary field and the design of the first motor embodying it are attributed to Nikola Tesla.

To produce a rotary field of force it is necessary to have two or more alternating currents differing in their phase relation

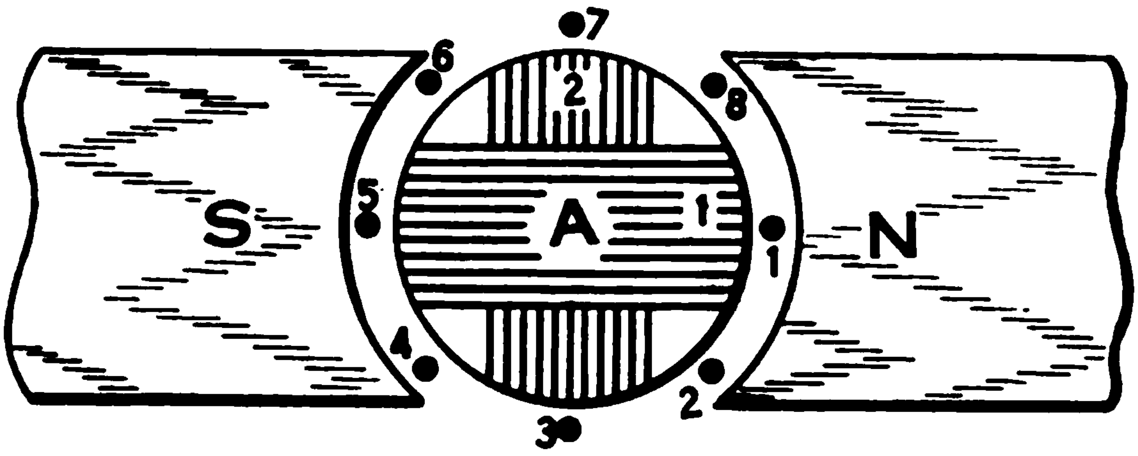


FIG. 818.

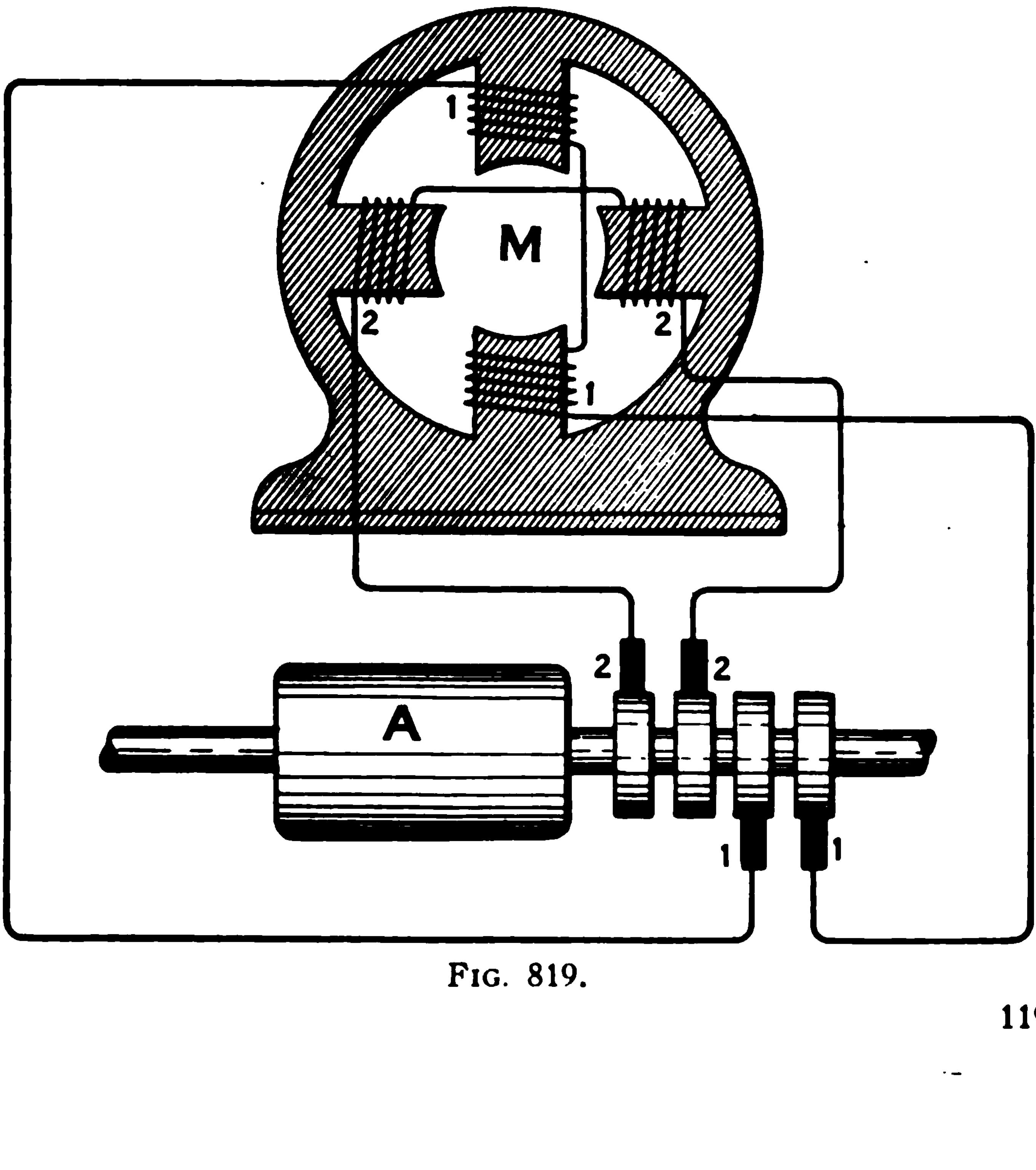


FIG. 819.

by some fixed angle. These currents cooperate to produce a resultant magnetic field which may be rotated in either direction desired and with a speed depending upon the frequency of supply.

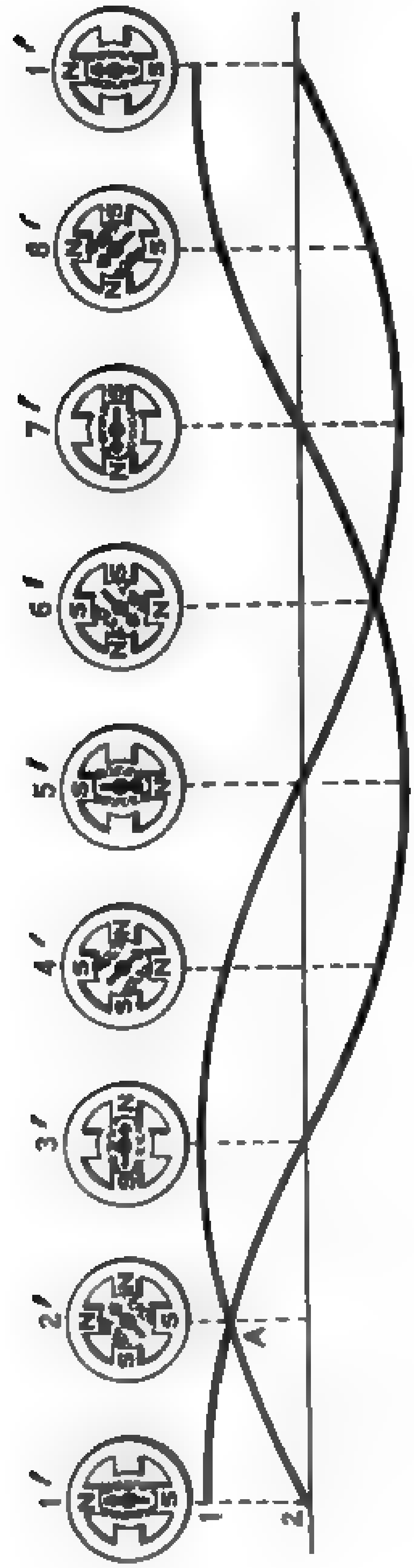


FIG. 820.—Illustrating the cooperation of two alternating currents differing in phase relation by 90° to produce a rotating field of force.

Consider an alternator, Fig. 818, with a stationary field *N-S* and a revolving armature *A*, having two coils, 1 and 2, placed mechanically 90° apart.

These two coils terminate upon four slip rings, Fig. 819, the coil 1 connecting to brushes 1-1, and coil 2 to brushes 2-2. The currents from these two coils will obviously be 90° apart in phase because of the fixed angular relation between the coils. The two currents are led over separate circuits to a motor *M*, having four stationary coils. The horizontal coils 2-2 are supplied from phase 2 of the alternator and the vertical coils 1-1 from phase 1. The two curves 1 and 2, Fig. 820, show the instantaneous values of the currents in the two phases of the alternator armature. In the position shown for the armature in Fig. 818 coil 1 is cutting lines of force at a maximum rate and therefore generating a maximum e.m.f. supplying a maximum current to coils 1-1 in the motor. This current is pictured at point 1′, Fig. 820, while coil 2, whose conductors are parallel to the flux and

therefore generating no current, is shown at point 2, Fig. 820. As the coils 1-1 of the motor are energized, a magnetic flux will be produced vertically between these poles, while the horizontal poles carrying no current will be dead. A permanent magnet or piece of soft iron placed in this field will assume a vertical position parallel to the lines of force. If the armature be advanced one-eighth of a revolution, the current in coil 1 of the alternator will fall and the current in coil 2 will rise. This will energize coils 1-1 in the motor to a lesser degree and coils 2-2 to an equal degree. This is shown at point *A*, Fig. 820, and the resultant magnetic field due to the four coils of the motor will be

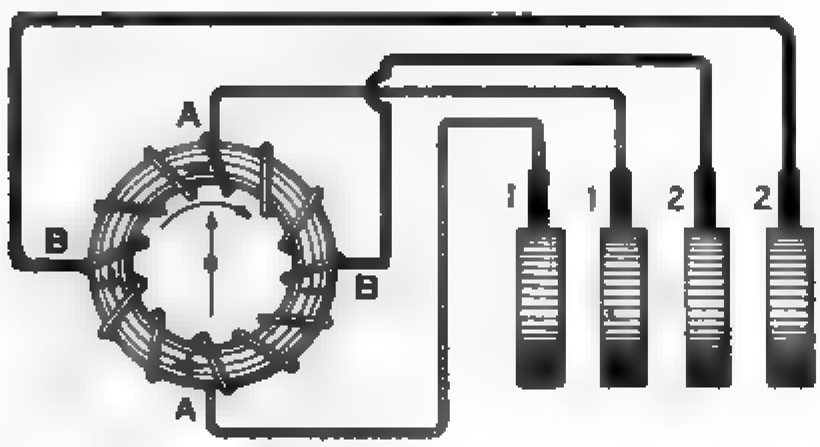


FIG. 821.—Illustration of connections from a two-phase source to a Gramme-ring winding to produce a rotating field of force.

advanced one-eighth of a revolution as in position 2′. The permanent magnet will then advance one-eighth of a revolution to place itself parallel to the field in its new position. If the armature of the alternator is successively advanced one-eighth of a revolution, the positions 3′-4′-5′-6′-7′-8′ and 1′ will be taken by the magnetic field, and the permanent magnetic needle will move with it. Thus the rotation of the armature of the alternator sets up two alternating currents which cooperate with each other through two sets of magnetic poles, producing an invisible magnetic field in the space between these poles which rotates in synchronism with the alternator armature itself. A simple apparatus to demonstrate this action may be constructed as in Fig. 821, where a Gramme-ring winding on a laminated core tapped at two diametrically opposite points by one phase and two other diametrically opposite points 90° away therefrom by the other phase, can be made to develop a rotating field of force when supplied with currents from a two-phase alternator.

Any mass of soft iron susceptible to magnetic induction placed within this field will be caused to rotate.

Three alternating currents differing in phase by 120°, as in Fig. 822, may likewise be made to cooperate to produce the rotating

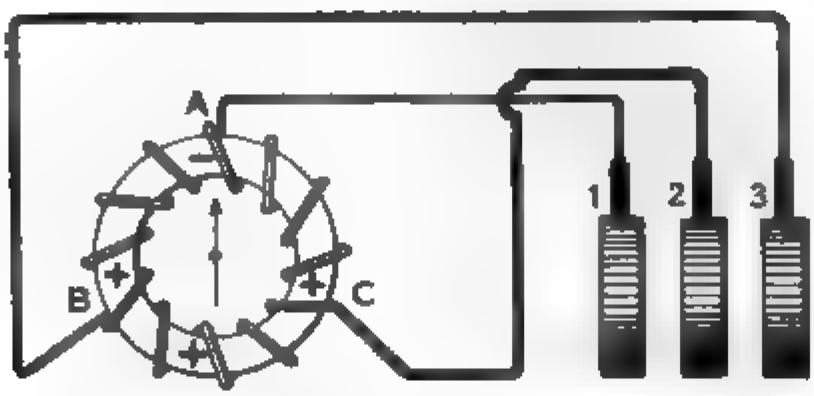


Fig. 822.—Illustration of connections from a three-phase source to a Gramme-ring winding to produce a rotating field of force.

field of force by connecting them to three points in such a winding 120° apart. While Gramme-ring windings are never used in actual motors, the simple connections illustrated show how readily the rotary magnetic field of force may be produced.

SECTION XVI CHAPTER II

ALTERNATING-CURRENT MOTORS

THE ROTARY MAGNETIC FIELD OF FORCE

1. Explain how two alternating currents differing in phase relation by 90 degrees can combine to produce a rotary magnetic field of force.

A. C. MOTORS

PRINCIPLES OF INDUCTION MOTORS

Polyphase Induction Motors

The rotary magnetic field of force is employed in both polyphase synchronous motors and polyphase induction motors. The polyphase synchronous motor with its field structure excited by direct current would not start, but if brought up to approximately synchronous speed before the exciting current was thrown on, it would run in the same direction as, and in synchronism with, the rotating field. The synchronous motor may be made

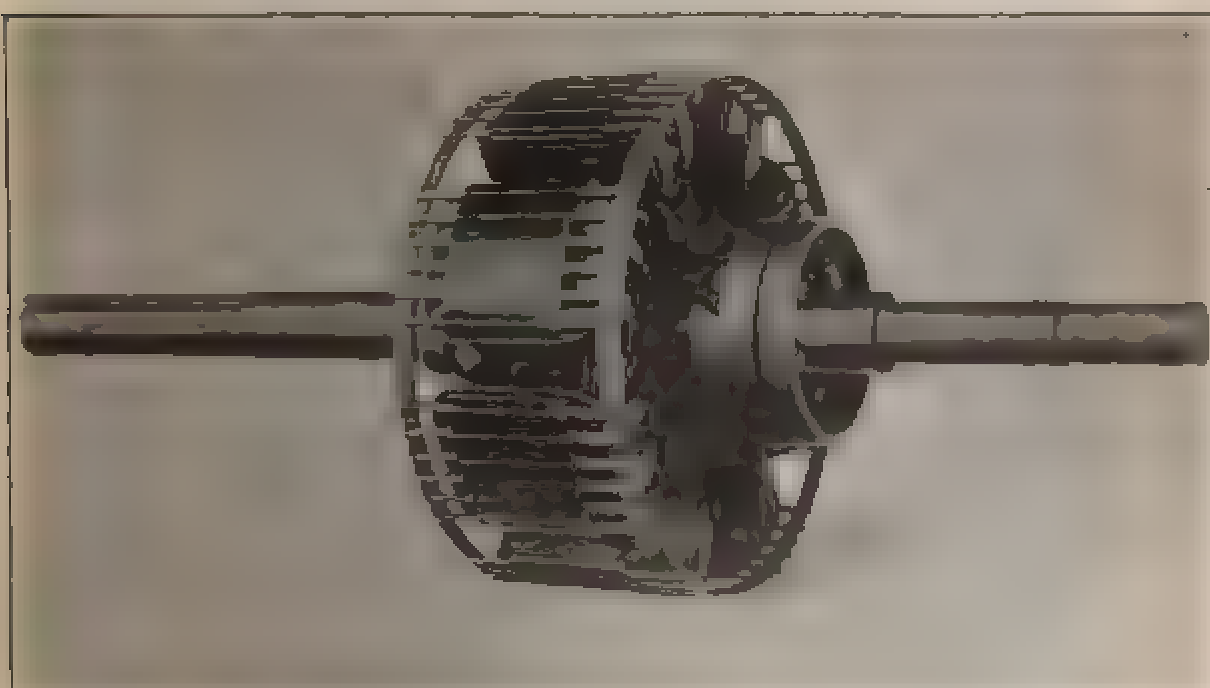


FIG. 823.—"Cage winding" imbedded in the pole pieces of the revolving field structure of a 75-K.W. Westinghouse synchronous motor.

self-starting by employing the induction-motor principle. Thus suppose that the poles of the field structure were subjected to the rotating magnetic field of force. As this field of force sweeps past them, eddy currents would be induced in these poles and, provided there was no direct current in the winding to establish fixed poles, the reaction of these eddy currents on the revolving field would cause the field structure to be dragged around after the rotating field of force. The torque, however, would be feeble,

It could be materially increased by providing the field poles with a short-circuited winding of low resistance similar to that of an induction motor. Such a winding, embedded in the pole faces of the revolving field structure of a 75-K.W. Westinghouse synchronous motor, is pictured in Fig. 823. The reaction of the induced currents in this system of conductors produces a satisfactory starting torque. When the revolving member has attained full speed the direct exciting current is admitted to the proper winding, and definitely established poles appear and the rotor locks into step at synchronism. Thereafter no currents are induced in the starting winding unless the rotor is loaded until it falls out of step.

A direct-current motor has the working current introduced into the revolving member by a pair of conducting brushes. In

Fig. 824.—Stator of Westinghouse type C. W. induction motor.

the induction motor the working current is produced in the revolving member through induction. The action in a **direct-current** motor is **conductive.** In an **induction** motor it is **inductive.** In this machine there are two distinct though closely related functions. First, a transformer action; second, a motor action.

The terms **"armature"** and **"field,"** commonly used with direct-current motors, are abandoned for alternating-current motors because of the similarity of the two members. They are dis-

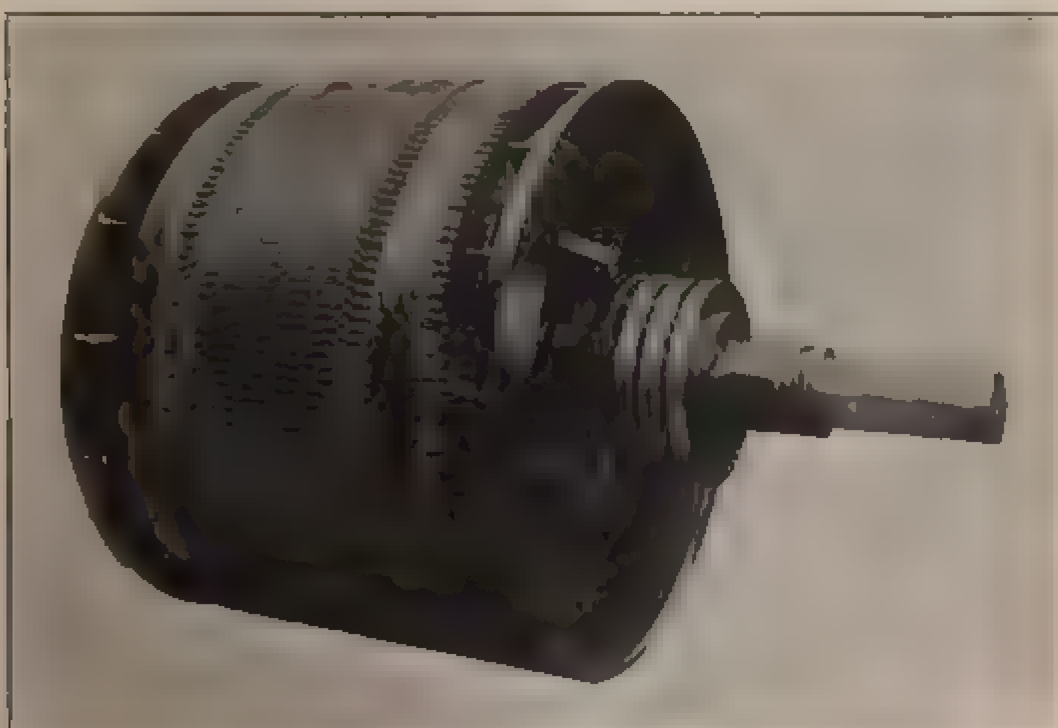


FIG. 825. Form-wound rotor of Westinghouse type C. W. induction motor.

tinguished as **"stator,"** the stationary member, and **"rotor,"** the revolving member. These two parts bear somewhat the same relation to each other as the primary and secondary of a transformer. The usual practice today is to make the stator the primary and the rotor the secondary, although these functions could readily be reversed. The stator of a Westinghouse type C. W. induction motor is shown in Fig. 824. A wound rotor for large and medium size Westinghouse induction motors is shown in Fig. 825. These rotors are of various forms, but in general they consist of an iron core on which is a system of conductors connected in various ways but always with the object of organizing the induced currents in such a manner as to produce the required magnetic polarity.

The theory of the manner in which current is induced in the rotor may be understood from a consideration of Fig. 826. Here it may be supposed that a rotating field of force, due to currents in a stationary winding, rotates from polar projections *A* to *B* to *C* to *D* in the direction of the arrow *K*. The lines of force due to this field are in the direction *D-B*. As the field rotates it cuts squarely across the conductors *E-F-G-H* of the rotor, which, for the moment, is stationary. This direction of cutting will induce currents which will flow toward the observer in the conductors *H-G* and away from the observer in the

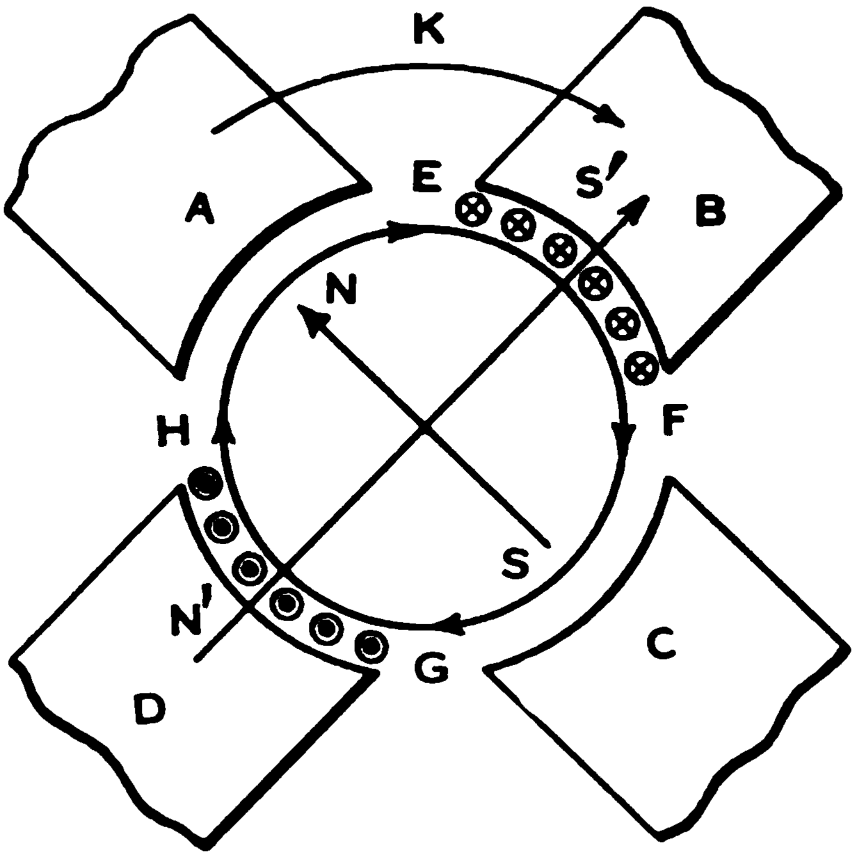


FIG. 826.—Relative directions of rotating field, induced currents in rotor, and resultant direction of rotation of rotor in induction motor.

conductors *E-F*. The direction of the magnetic resultant of these induced currents will evidently be *C-A*. This would tend to produce a north pole on the rotor at *N*, which would be attracted by the south pole of the stator *S'*, while the north pole of the stator *N'* would repel the north pole *N* of the rotor, urging it in the direction of the rotating field. If the rotor traveled as fast as the rotating field, there would evidently be no induced voltage or current and therefore no torque, for in order to induce voltage there must be relative motion between the rotor and the rotating field. It is therefore necessary that the rotor shall run at a speed less than synchronism. This fall in

speed below synchronism is technically known as the "**slip.**" It is usually quite small, varying from 2 to 5 per cent. At no load the rotor travels at practically synchronous speed. As the load increases the slip increases. The greater the slip the greater the rate of cutting of the rotor conductors, the greater the induced e.m.f., and the greater the secondary current. Up to a certain point the torque also increases with the increase in slip.

If the rotor stood still while the rotating field traveled 3,600 r.p.m. due to a frequency of 60 cycles in a bipolar field, the frequency of the induced current in each conductor in the rotor

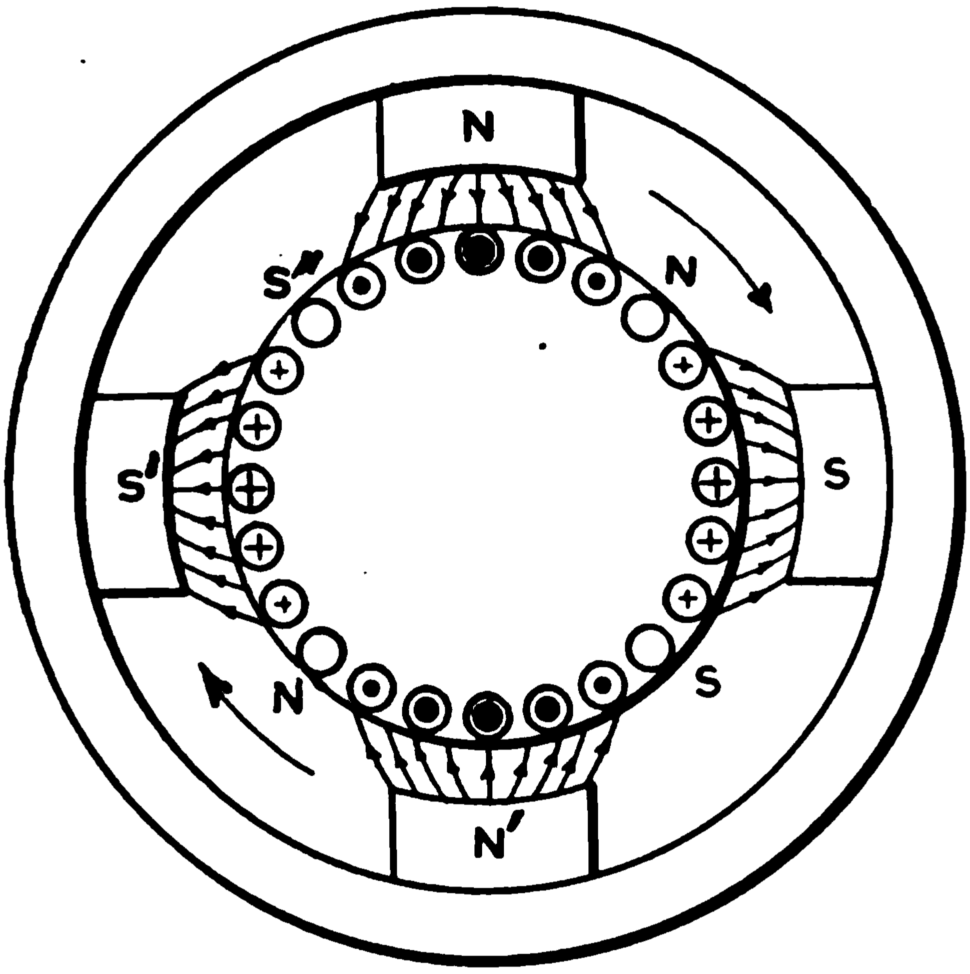


FIG. 827.—Relative magnitude and position of currents in rotor of induction motor if rotor possesses resistance only.

would likewise be 60 cycles. If the rotor had no load, it would run at practically synchronous speed. There would then be practically no slip, and the frequency of the current induced in each conductor of the rotor would be practically zero. If the load was such as to cause the rotor to slow down to 5% below synchronous speed, the frequency of the currents induced in the rotor would be 5% of 60 cycles, or 3 cycles per second.

A clear conception of the relation of the current in the rotor conductors at any instant with respect to the magnetic polarity of the field may be gained from an examination of Fig. 827.

If the rotor winding possessed no inductance but merely resistance, the field rotating in the direction given, the induced voltage and resulting current in the conductors would be a maximum when under the center of the stator poles. The resulting polarity of the rotor would then be as shown. These poles would react with a maximum effect upon the poles of the rotating field to produce torque. If, on the other hand, the rotor winding possessed great inductance and comparatively little resistance, the currents would not reach their maximum value in the conductors

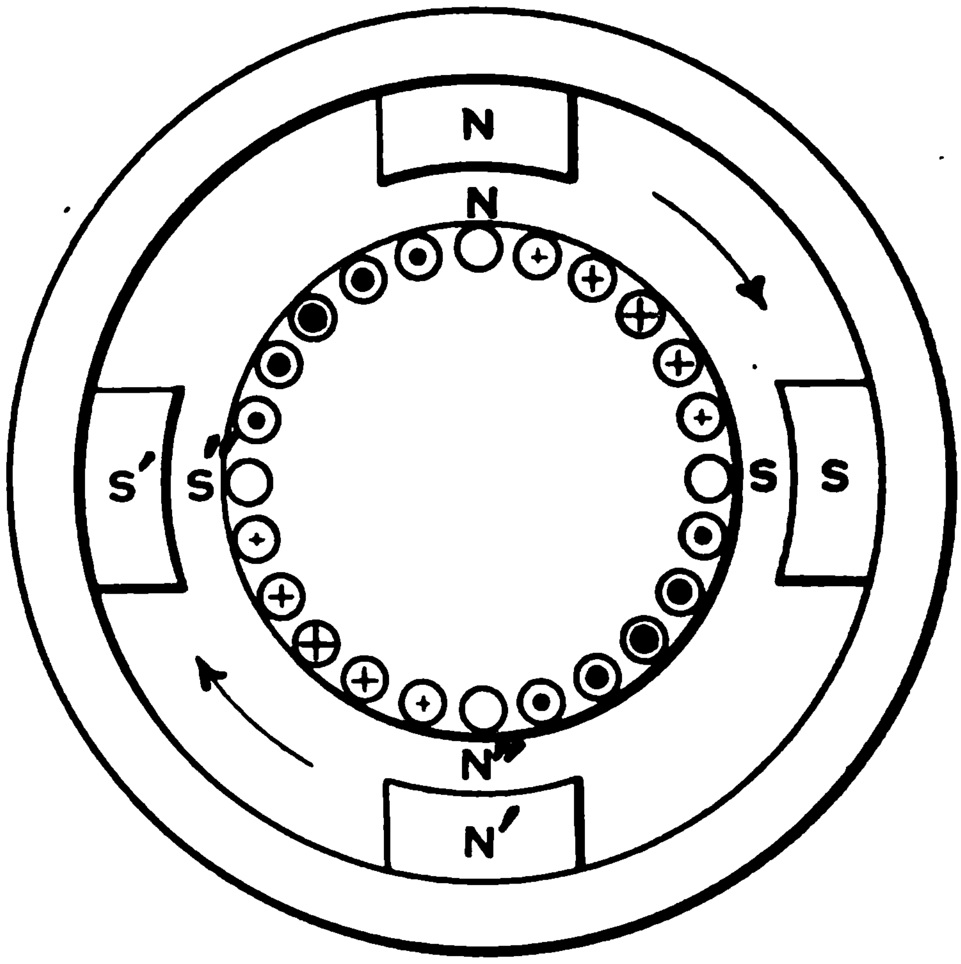


FIG. 828.—Relative magnitude and position of currents in rotor of induction motor if motor possesses inductance only.

until located as shown in Fig. 828. The resulting polarity of the rotor would now be in line with the poles of the stator, and the torque of the motor would be zero. As the **frequency** of the current **in the rotor is very great when starting,** the **reactance** is **great.** Hence the **torque is comparatively small.** As the rotor speeds up, the **frequency** of the current **in the rotor and consequently the reactance** therein **go down** and the angular displacement between the poles of the rotor and the poles of the stator increases from that shown in Fig. 828 to that shown in Fig. 827, and the **torque increases.**

As already explained, there will be no slip, no induced e.m.f., no current and no torque when the rotor runs in synchronism with the rotating field. If a load is applied, the rotor commences to slip. As the slip increases the induced e.m.f., current and torque also increase, and the increase in torque would be in direct proportion to the slip were it not for the demagnetizing effects of the rotor currents. The magneto-motive-force of the rotor is opposed to the magneto-motive-force of the stator, and as the induced currents rise the reaction causes a leakage flux to occur in the gap space between the rotor and stator. This is similar to the leakage flux between primary and secondary windings of an ordinary transformer. As a result, when the rotor currents increase, the demagnetizing action increases and the magnetic leakage rises until, when the rotor current is large, the flux through the rotor becomes smaller and the resultant torque may actually fall instead of rising with an increase in secondary current. Also, as explained before, the rotor reactance increases with the slip. An increase in reactance affects the time phase angle between the currents in the rotor and in the stator so as to further decrease the torque between the two.

For every particular motor there is a certain slip at which the maximum torque is exerted and beyond which point the reaction of the rotor becomes so great that the torque decreases with an increase of slip. The actual point where this occurs depends on the design of the motor.

The starting torque—that is, the rotating effort with 100% slip, as when the motor starts from rest—will depend very largely on the resistance of the rotor winding. If the **secondary conductors** are of copper and therefore have a very **low resistance,** the **current at start** is very **large.** The magnetic reaction will be great and the **resulting torque small.** If, on the other hand, the **rotor circuits** are **of high resistance,** the **current** induced **at** a **standstill** will be **limited** in amount by the resistance of the rotor winding and the **starting torque** may be **relatively high.** This is because the rotor current will not batter down and deflect the stator flux so much as before. Also the reactance of a rotor at a standstill is practically fixed by the mechanical design regardless of the resistance of the conductors. If these conductors are of high resistance, the power factor of the rotor current is higher, and the phase relation between the rotor and

stator currents improves so as to assist in increasing the starting torque, although the current in the rotor has decreased.

The torque in the motor depends upon the actual flux which crosses the rotor.

A motor with a **high-resistance rotor** will develop its **maximum torque at the start** or at very low speed, but the efficiency and **regulation** of such a motor would be very **poor** as the high

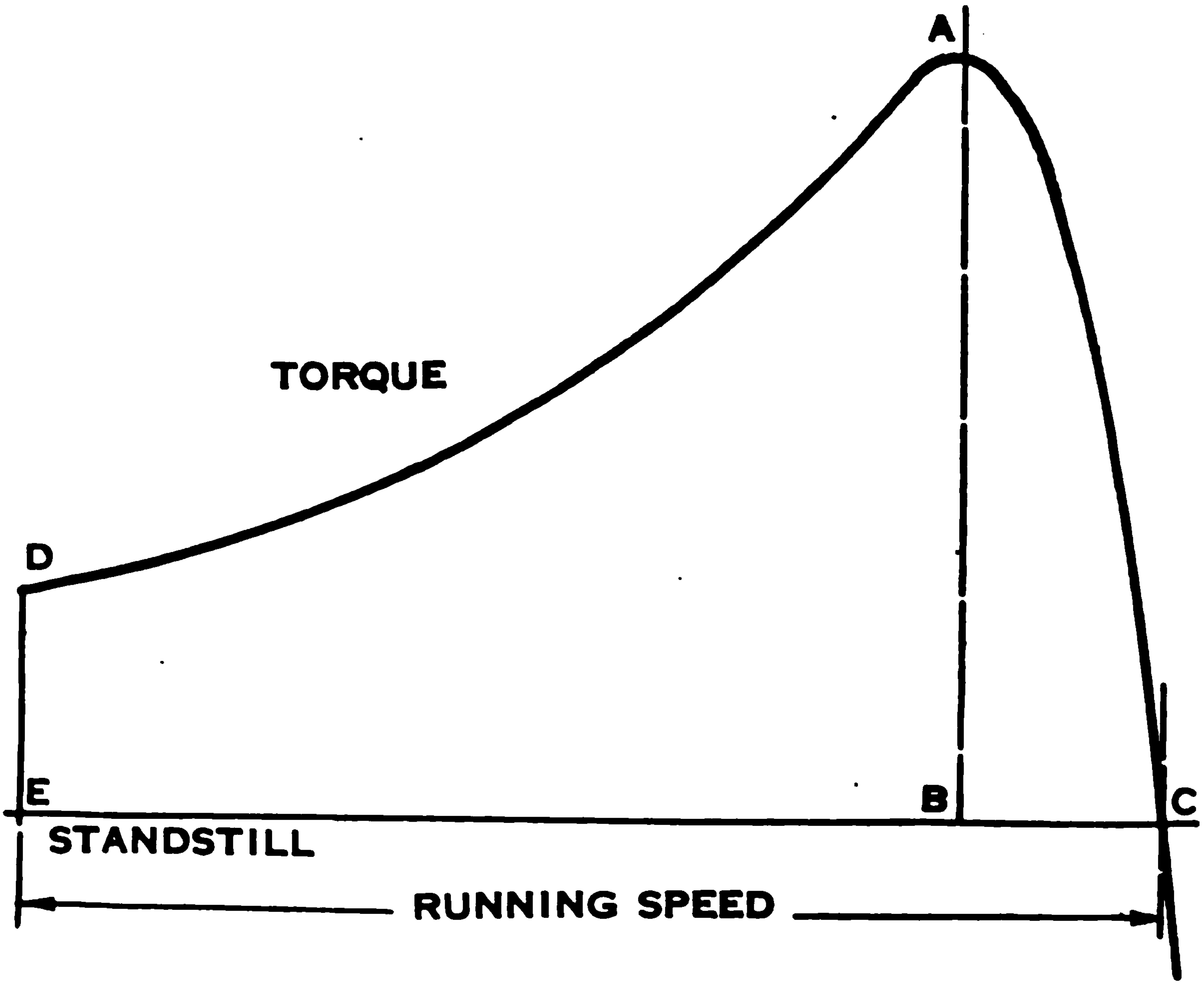


FIG. 829. -Torque characteristic of induction motor between synchronous speed and standstill.

resistance winding would produce a greater slip and I^2R loss at normal load.

A motor with a **low resistance rotor** would exert its **maximum torque** at **high speed.** Such a machine would have a high efficiency and small slip at normal load but would develop a very **poor starting torque.** The torque, speed and general performance of an induction motor can thus be changed considerably by observing the above-mentioned points in design.

Fig. 829 is a torque curve for an induction motor. The line *E-C* represents variation in speed from standstill to synchronism.

At synchronism *C*, the motor's torque is zero From this point the speed falls off and the torque rises rapidly as the slip increases, reaching a maximum at the point *A* with a slip equal to *C-B*. This particular point is called the **"pull-out"** torque or **"break-down"** point If loaded further the motor shuts down, the torque curve falling rapidly until, at the point *D*, when the motor is standing still, there is very little torque

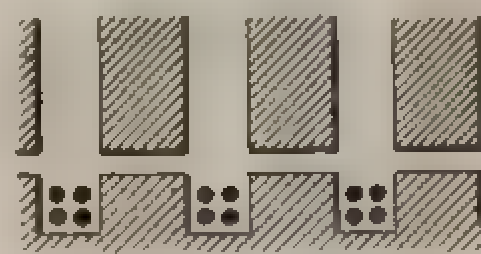


Fig. 830.

The induction motor is approximately a constant speed machine resembling in this particular a direct-current shunt motor Its starting torque, however, is smaller, and its drop

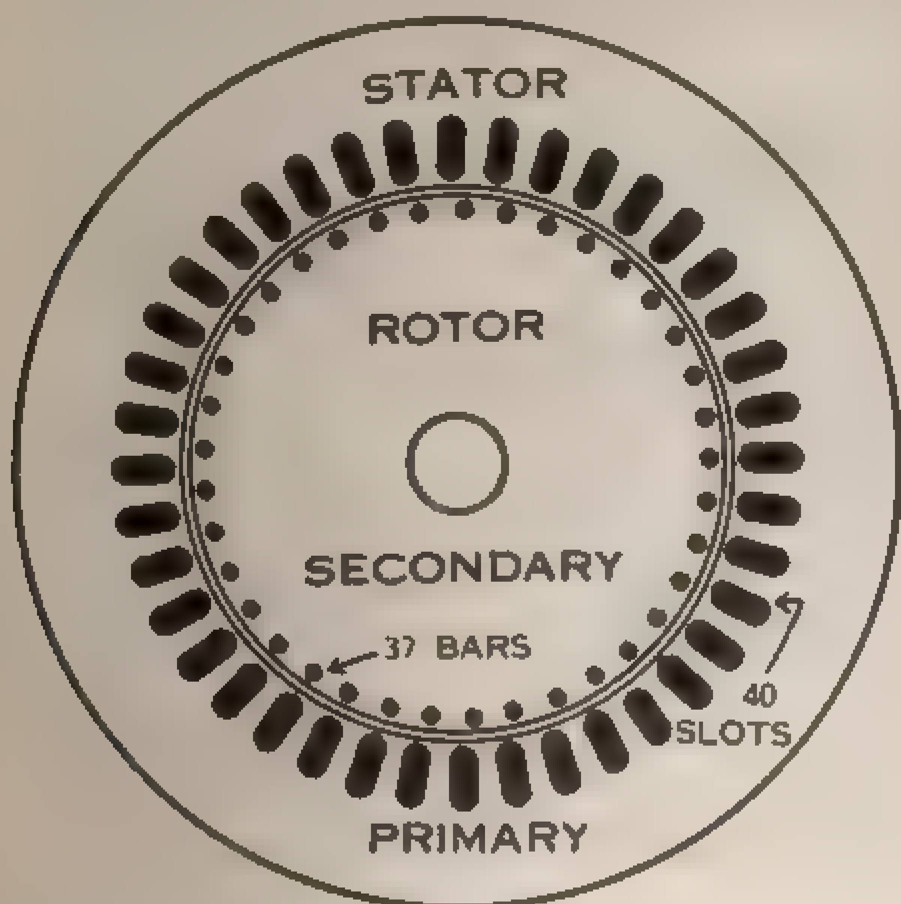


Fig. 831.

in speed less than in a shunt motor It also possesses the peculiar feature of pulling out and shutting down at a critical point, which is unlike a shunt motor.

The number of slots in the rotor should never be equal to or a multiple of the number in the stator as in Fig. 830, as under

Fig 832

such circumstances the rotor teeth and stator teeth would line up so as to make the magnetic reluctance less in the position shown. This would exert a force opposing rotation, as any effort to turn would increase the reluctance of the path. This would prevent smooth operation, as the flux value would vary as the slots passed and also might prevent starting the rotor in certain positions. The number of rotor slots is therefore always made prime to that of the stator, as in Fig. 831; then the reluctance of the magnetic circuit across the span of one stator pole is not materially altered by any position of the rotor.

Three forms of slot construction are employed for induction-motor stators. In section 1 of Fig. 832 is shown an open slot construction with wooden wedges employed to hold the coils in position. This permits the use of form wound coils which are the strongest mechanically and are well insulated. The flux lines passing from stator to rotor concentrate in the comparatively narrow tooth, and as they separate in the air gap the average length of the path is increased, necessitating a greater magnetizing current. This involves a low power factor.

Section 2 illustrates the partially closed construction. Form wound coils completely taped up cannot be employed here, but the portion which is placed in the slot must be threaded in, one or two conductors at a time. This does not permit of getting as much wire in the slot nor of insulating it as well as in the preceding method. It also makes it more difficult to effect repairs. The overhanging edges of the slot, however, provide a greater tooth area through which the flux is distributed. This enables the lines of force to travel straight across the gap by the shortest possible path. As a result the magnetizing current is lowered and the power factor is improved.

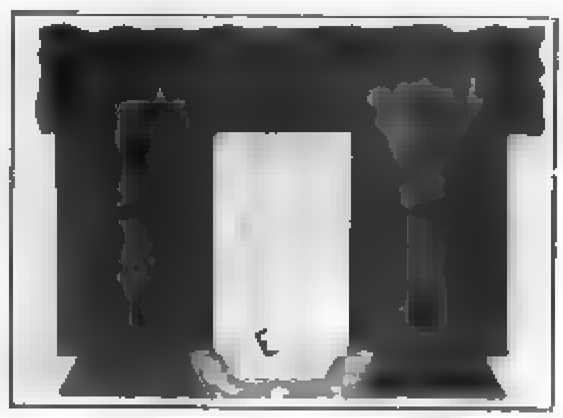


Fig. 833.

Section 3 illustrates a construction that embodies both the advantages and eliminates the disadvantages in the two other designs. It involves the use of a magnetic bridge, *E*, Fig. 833, which consists of a wedge of soft steel with a small air gap in the

center, which is driven into place after the formed coil has been placed in the slot. It gives the advantage of the open slot construction which admits of better insulated and more easily placed coils, and at the same time gives the high power factor obtainable with the partially closed slot but is a more costly construction than the partially closed slot type.

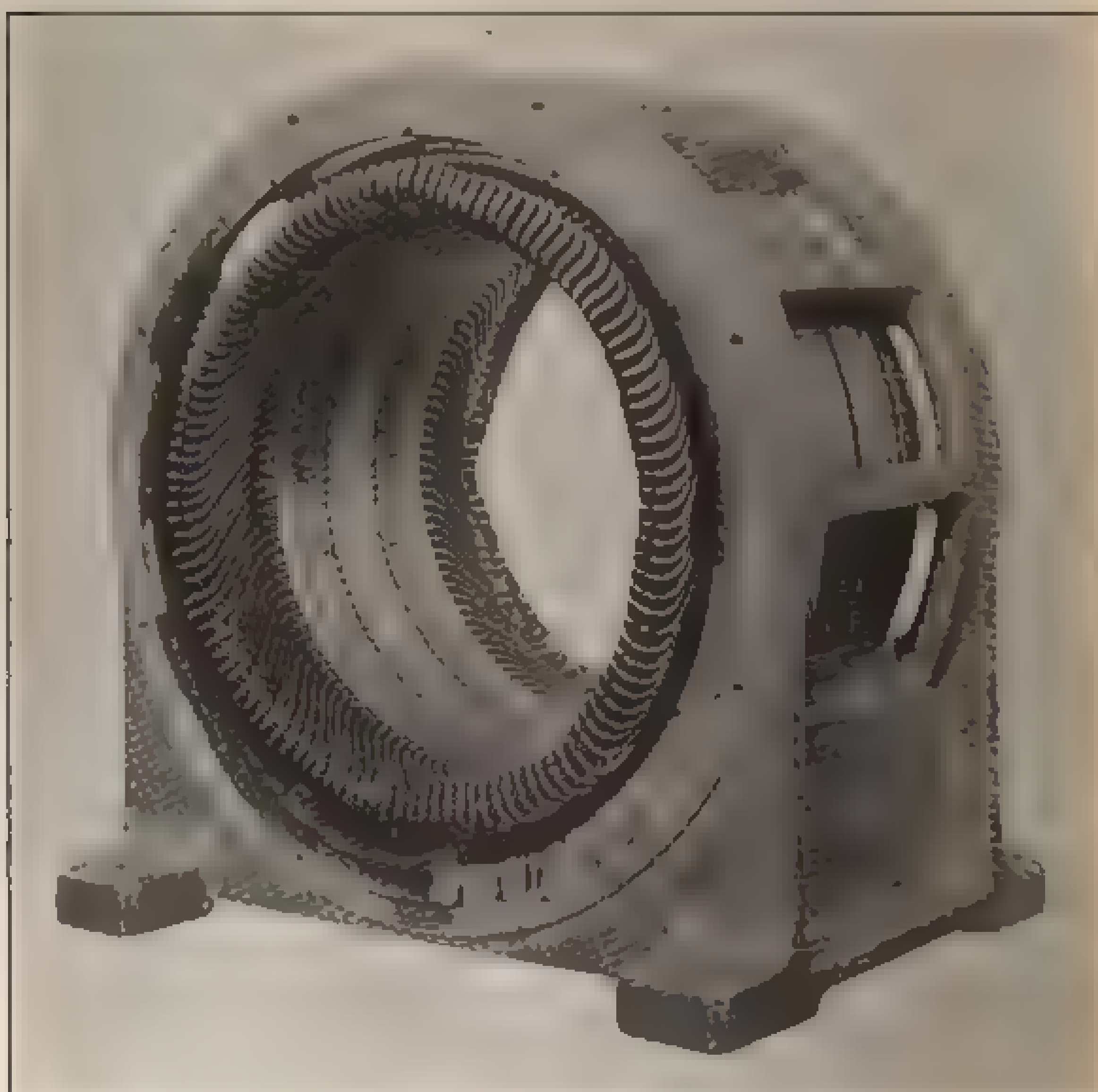


Fig. 834.

Induction motors are usually provided with a stator of the general appearance of Fig. 834, which pictures the General Electric type K.T. construction. For these stators three forms of rotors are available. The General Electric Company designate these as the forms *K*, *L* and *M*. The form *K* rotor is pictured in Fig. 835. It consists of a number of parallel conductors placed in slots in a laminated core, the ends of these conductors in the rotor pictured being welded to massive copper rings which

connect the entire number in parallel. In the absence of the iron core such a winding would resemble in appearance the well-known squirrel cage. It has therefore been named the **squirrel-cage** rotor or the **cage-wound** rotor. The conductors are usually massive bars of copper, either round or square in cross-section. Bare conductors are frequently employed, it not being necessary to insulate them. The reason is that the induced voltage is exceedingly small, and the difference of potential between any

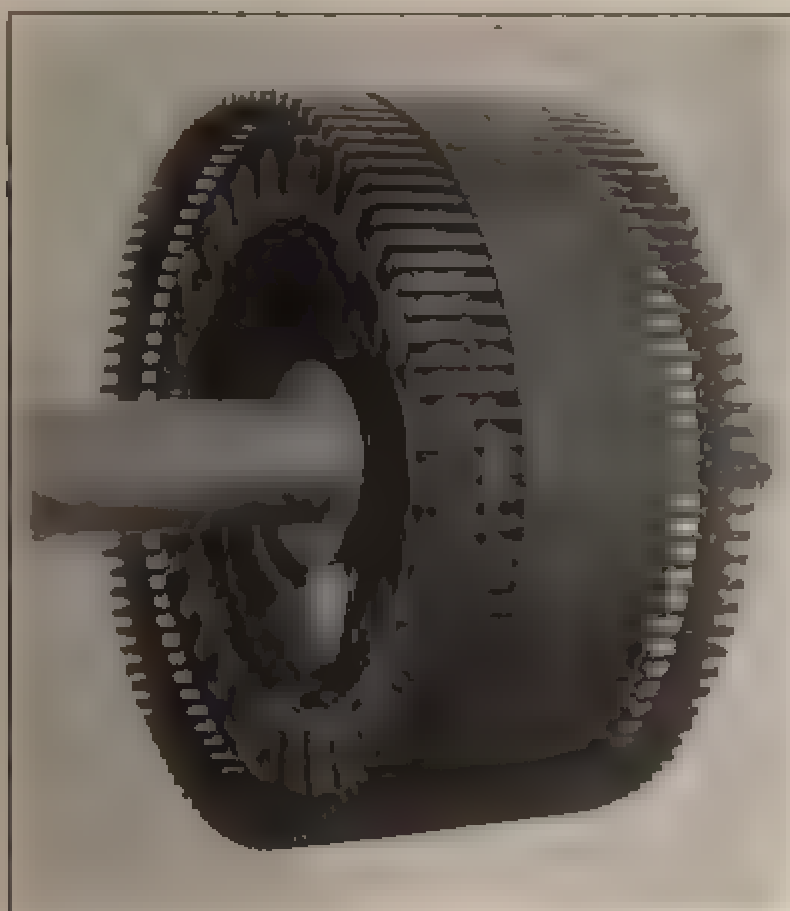


Fig. 835.—General Electric form K, cage wound rotor for induction motor

two points, such as the middle of one conductor and the middle of an adjacent conductor in front of one pole, is practically zero. The current therefore is urged in a sheet from one end of the rotor to the other across the entire space of one polar area until it reaches the connecting ring on the end, whence it divides and returns in series with the conductors in front of opposite stator poles adjacent thereto.

Various methods of connecting the conductors to the end rings have been employed. As the currents are large and the voltage small, the resistance of the connection must be a minimum. In

small rotors the connection is sometimes riveted and soldered. In large types the end ring has been connected by a bolt and nut to each conductor. In still other types the end ring has been welded or brazed to each conductor. Finally the end ring has been cast from molten metal directly onto the conductors themselves, thus insuring perfect contact at all times. Rotors have also been made in which the conductors and end rings are of aluminum, all being cast in solidly after assembling the iron structure of the rotor

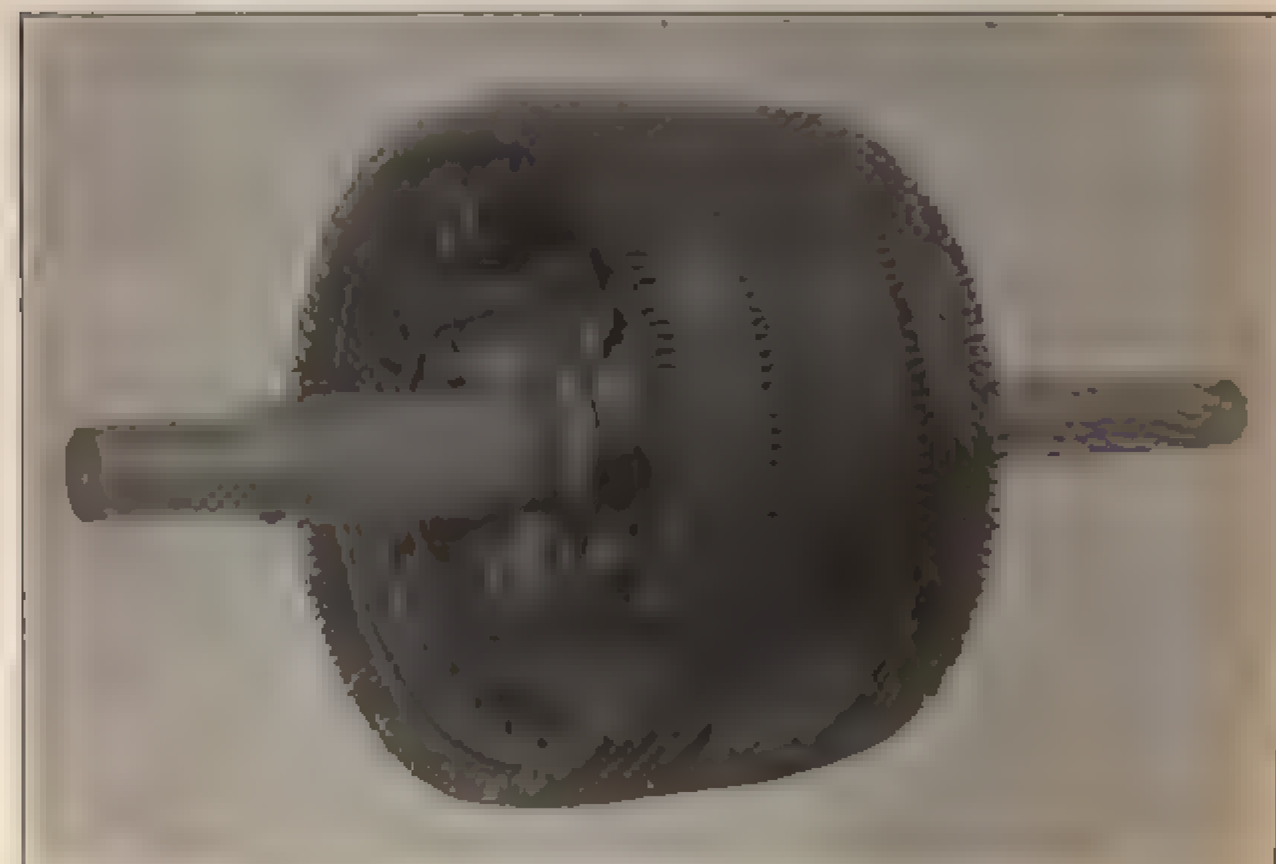


FIG. 836. General Electric form L rotor for induction motor

The form *K* rotor represents the most rugged possible construction With no insulation, with no soldered joints, with massive conductors and no commutator, slip rings or brushes, there is practically nothing to get out of order. The rotor is virtually indestructible and will last indefinitely. Its chief disadvantage is that it is not capable of developing a high starting torque unless high resistance conductors or end rings are employed, with consequent poorer efficiency and regulation.

Because of the small load which the form *K* rotor is able to start the load is often attached to the pulley, which includes a

friction clutch, enabling the rotor to start freely. An expanding ring within the clutch, operating by centrifugal force, gradually comes in contact with an outer band which it grips by friction and thus starts the load smoothly.

In the form *K* rotor the currents flow rather promiscuously, and the magnetic polarity is not as sharply defined as could be desired.

The form *L* rotor, Fig. 836, is wound with definite poles established by formed coils placed in the rotor slots and constituting a winding which may be practically a duplicate of the stator winding. The currents induced therein flow in definitely organized paths, and as the winding is well insulated the poles are more sharply defined and a better starting torque is developed.

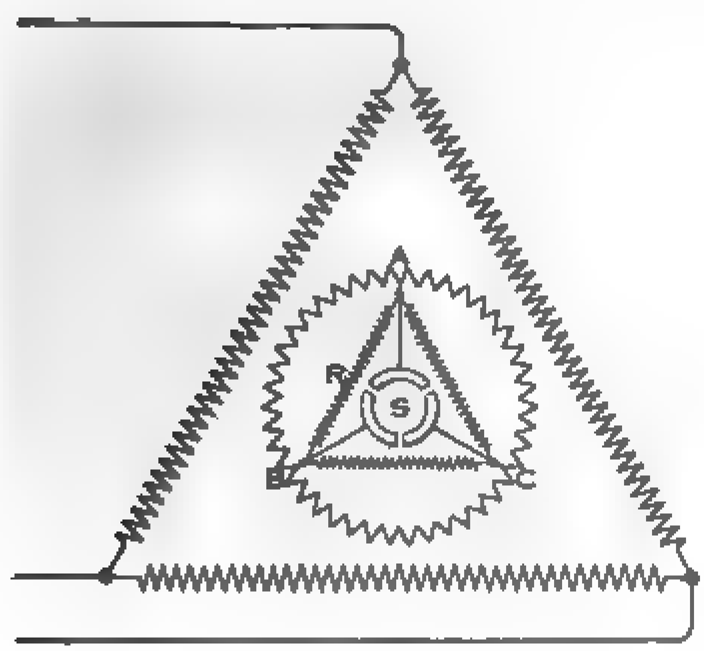


Fig. 837.

Within the rotor, however, there is mounted a three-phase rheostat *R*, Fig. 837, connected in either Y or Δ and tapped to the three terminals *A*, *B*, *C* of the rotor winding. This resistance is sufficient in amount to limit the induced currents in the rotor winding at the start to full-load value. Under these conditions the motor is enabled to develop full-load torque at the start. This is a decided advantage over the cage-wound rotor, which would require approximately four times full-load current to produce full-load torque when starting. When the motor is up to speed, a button operating a rod through the center of the rotor shaft is arranged to connect all three segments of the switch *S*, together, which short-circuits the starting resistance and con-

verts the rotor into the equivalent of a cage winding. In some types of motors employing this style of rotor the switch S operates automatically by centrifugal force when the motor approaches synchronism. Thus R constitutes a one-step starting box which

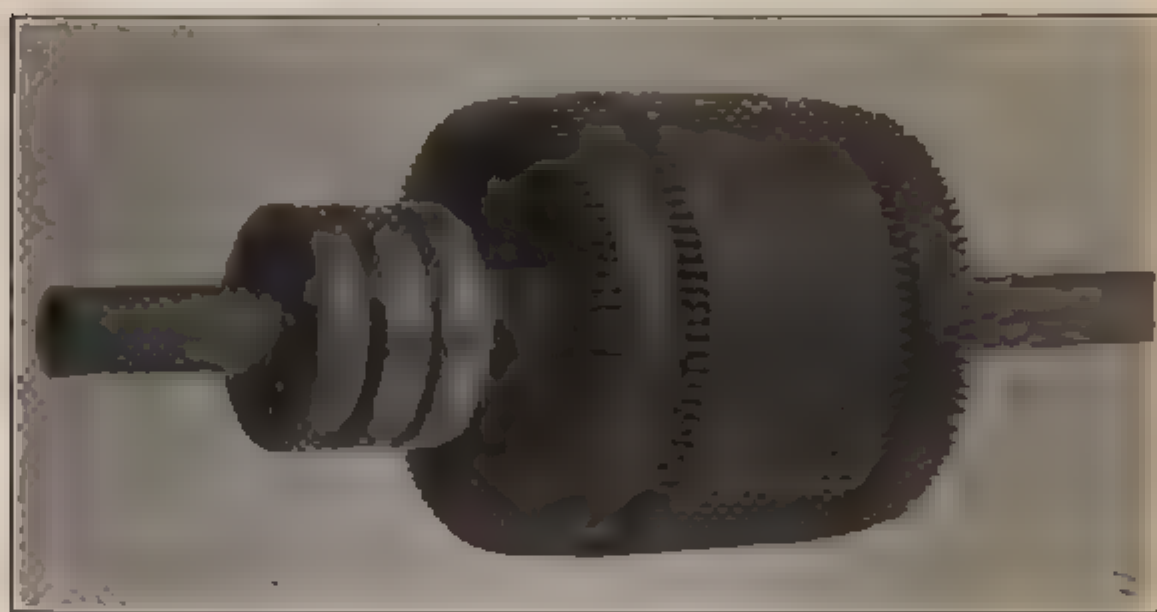


Fig. 838. General Electric form M rotor for induction motor.

very effectively reduces the initial current in the rotor and therefore in the stator Where it is important that the line voltage should not be affected by heavy starting currents or where the generator capacity is limited, the form L rotor may be used to advantage.

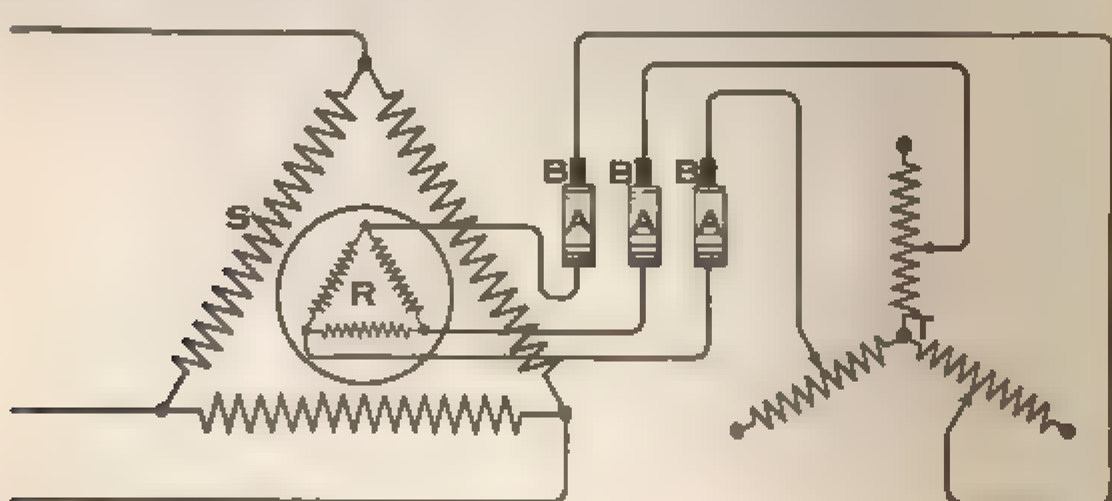


Fig. 839.

The form M rotor, Fig. 838, is practically identical in construction with the form L, except that the starting resistance is externally placed instead of internally. In Fig. 839, S is the stator winding and R the rotor winding. The three terminals

of the rotor lead to three slip rings, *A-A-A*, from which brushes *B-B-B* conduct the current to an externally placed Y-connected rheostat *T*, having three arms. The advantage of this arrangement is the great flexibility permitted. The three arms of this rheostat are all connected to one handle as in Fig. 840, which permits of any adjustment of the secondary current desired. The current enters through the leads *A-B-C* and the main line switch and passes thence to the stator. The induced currents from the rotor are led out from the slip rings and thence through the starting rheostat. By manipulation of the rheostat the rotor can be made to start any load within reasonable limits, requiring either less or more than full-load torque, with a minimum of current. The form *M* rotor is preferable for cranes, hoists and electric elevators.

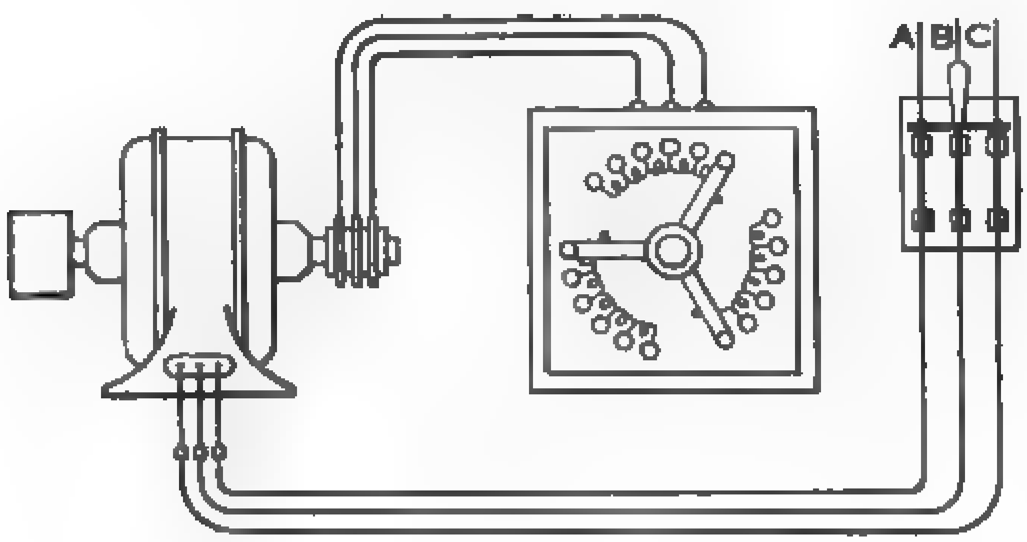


Fig. 840.

If the external rheostat has sufficient carrying capacity, it may be arranged to remain continually in circuit and thus give speed control under various loads similar to that which would be obtained from a shunt-wound direct-current motor with a regulating rheostat in its armature circuit.

Polyphase motors employing the form *K* cage-wound rotor are often thrown directly across the line without any starting device whatever in sizes up to 5 horse power. Above this size a starting compensator is employed. This is in effect a three-phase auto transformer, Fig. 841, of the core type, each leg having a single winding. The lower ends of these windings connect to a common point, while the upper ends extend to the source of supply. Taps are taken off from the winding at various

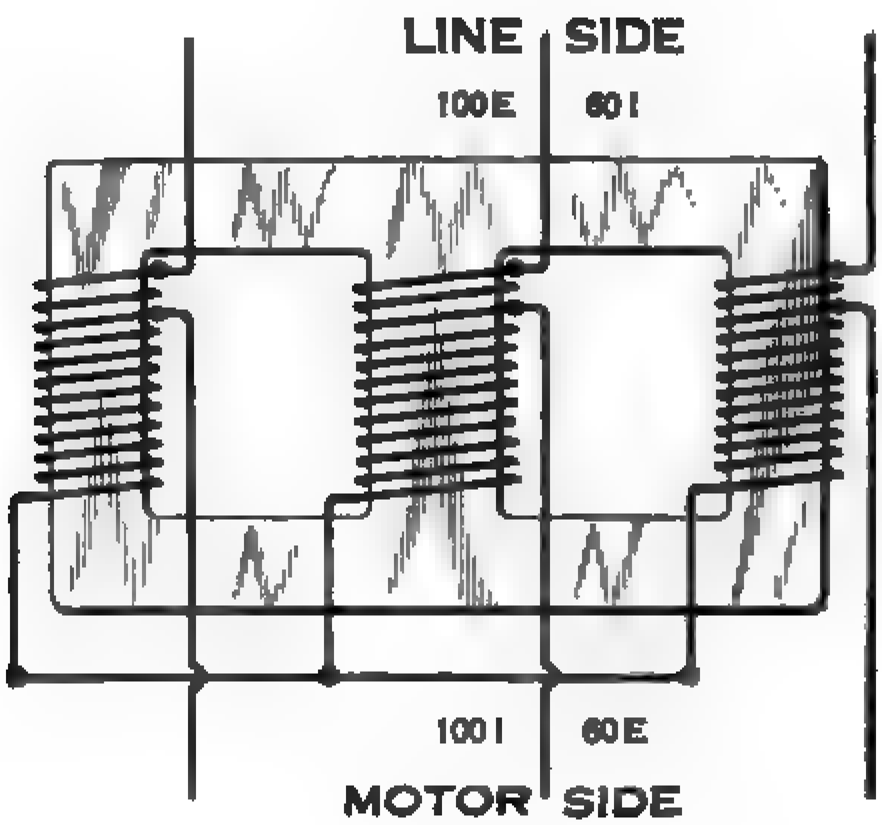


Fig. 841.

points according to the voltage, current and torque required by the rotor when starting. Fig. 842 shows the arrangement.

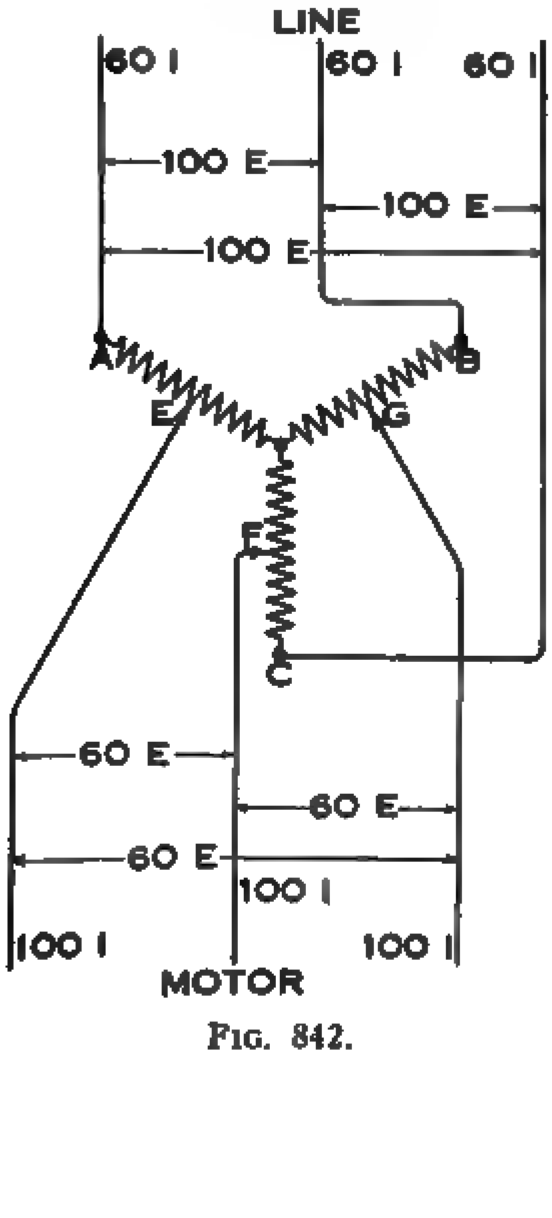


Fig. 842.

Here *A*-*B*-*C* represent the three windings of the compensator. Let 100 volts be applied across each phase of the line side. Assuming a current of 60 amperes to flow through each line wire into the compensator, taps could be taken off at *E*, *F* and *G* which would supply 60 volts on the motor side and 100 amperes in each line wire. Thus, by the transformer action effected, a comparatively high voltage and small current is changed into a comparatively low voltage and large current, with practically no loss. This gives the large current on the motor side required to produce the necessary starting torque. Compensators are generally provided with taps

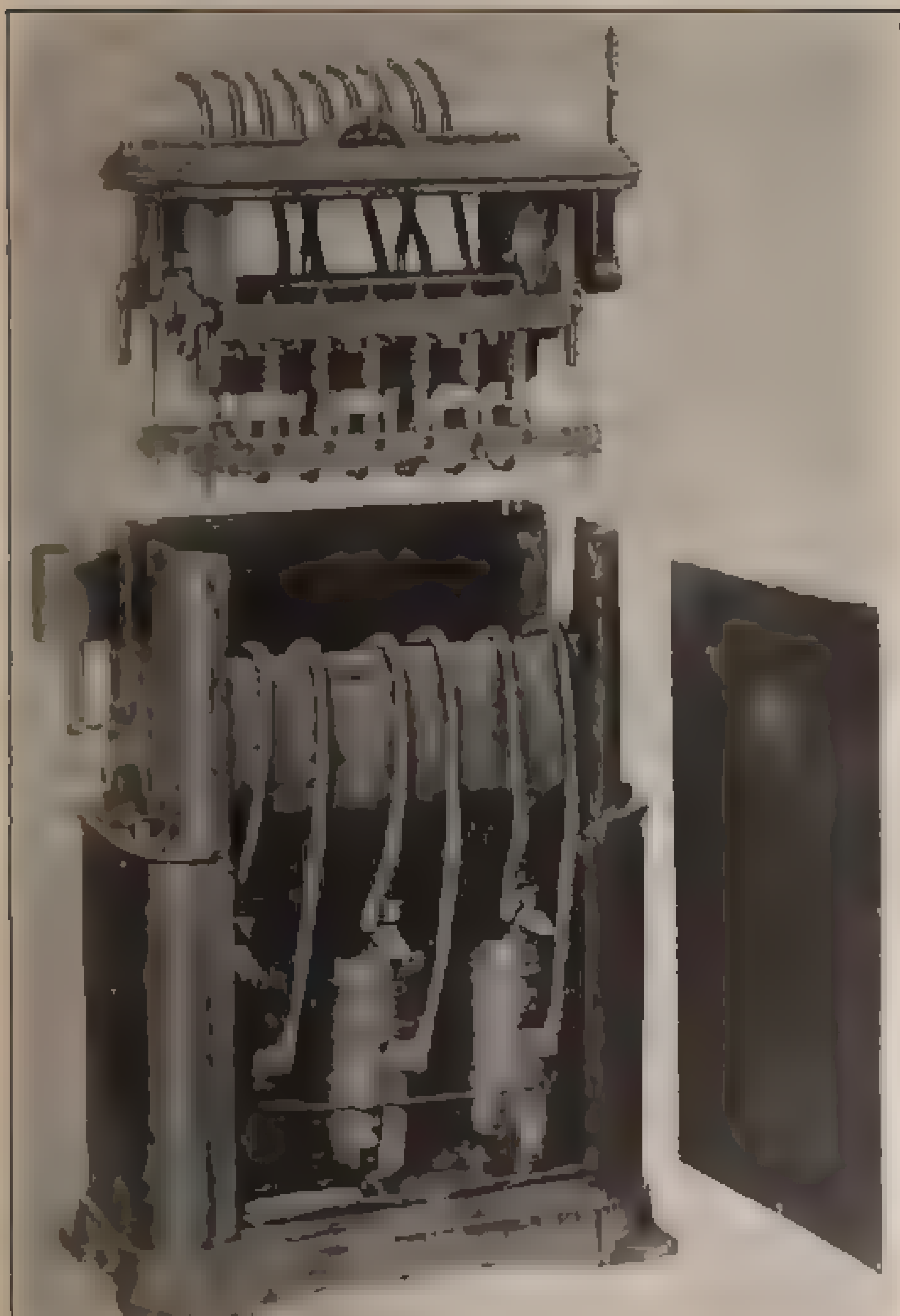


FIG. 843.—General Electric starting compensator for cage wound induction motors.

which will furnish the motor with 40 to 60 or 80% of the line voltage. The general relations between full-load current and full-load torque are shown in the following table:

Up to 15 H. P.	Per cent of rated E.M.F.	Per cent of full load	
		Current	Torque
1st tap	40	112	32
2nd tap	60	250	72
3rd tap	80	450	128
No compensator	100	700	200

The above represents the percentage of line voltage and current on the line side. Between the compensator and the motor the current is correspondingly more and the voltage correspondingly less. These values vary somewhat with the design of the motor.

The actual appearance of a General Electric Compensator is shown in Fig. 843. The throw-over switch for changing from intermediate to line potential is shown at the top. The no-voltage release coil is shown on the side at the left.

In place of a compensator a three-phase starting rheostat could be employed which would lower the voltage and improve the power factor under which the starting current was drawn. With such an arrangement, however, the gain in current due to transformer action of the compensator would be lost.

It must be borne in mind that the object of the compensator is to reduce the current drawn from the line at start by reducing the potential. Without the compensator, the current taken by the motor at start would be approximately seven times normal as indicated in the above table.

SECTION XVI CHAPTER III

ALTERNATING-CURRENT MOTORS

PRINCIPLES OF INDUCTION MOTORS

1. Is the rotary magnetic field produced in polyphase synchronous motors? Is it essential?

2. What is the direction of rotation of the rotor of an induction motor with reference to the rotating field. Explain fully by means of sketch.

3. What would be the amount of current induced in the rotor at synchronous speed?

4. What is meant by the "slip" in an induction motor? What determines the amount of slip? What effect has the slip on the torque and secondary current?

5. Why is the torque of an induction motor so poor when starting? How can it be improved?

6. With what D. C. motor does the regulation of an A. C. induction motor compare? Which regulates the better? What points in the design of an induction motor would improve its regulation?

7. What are the relative effects of low resistance and high resistance rotors upon the starting torque, efficiency and regulation of induction motors.

8. What relation should exist between the number of slots in the rotor and the number in the stator? Why?

9. What are the relative advantages of open slots and partially closed slots for induction motors?

10. Explain the construction of the "cage-wound" rotor. What are its advantages and disadvantages? How are the end rings attached?

11. Explain the construction of the "form-wound" rotor with internally located starting box. What are its advantages and disadvantages? How is the starting resistance cut out?

12. Explain the construction of the form-wound rotor with slip rings and externally located starting box. What are its advantages and disadvantages.

13. Explain the principle and advantages of the inductive compensator for starting induction motors with cage-wound rotors. Sketch.

14. How may the starting torque of an induction motor employing the compensator be altered?

A. C. MOTORS

PRINCIPLES OF INDUCTION MOTORS

Single-Phase Induction Motors

The rotating field produced in polyphase motors is inherently present in such machines and is symmetrical in form and magnitude, and if the motor travels at synchronous speed there will be no current induced in its conductors.

Pure single-phase motors have but a single winding, which may be connected up for any desired number of poles. Such a motor is not self-starting. If it is provided with a cage-wound rotor and once started or brought up to approximately synchronous speed, it will continue to run in the direction in which it was started because of a rotating field that is induced by the reaction of induced currents in the rotor.

A single-phase motor would have current in its rotor at practically synchronous speed, this current being necessary to produce the magnetism required for the rotating field. The field of the single-phase motor is elliptical in form instead of circular, the actual shape of the ellipse being determined by the speed of the rotor compared with synchronous speed. As it approaches synchronism it becomes more and more nearly circular.

Consider a bipolar field, Fig. 844, excited by an alternating current, having at a particular instant the polarity, *N-S*, the resultant flux being shown by the vertical arrow. Let the rotor *R* be forcibly driven by mechanical means across this field in the direction of the curved arrow. The direction of the e.m.f. generated in the conductors *A-B* will be as shown.

As this is a rotational voltage its maximum values will coincide with the maximum value of the main field flux—that is, it will be in time phase with it. But as this voltage produces a current which tends to produce a flux along an axis at right angles to the main field, there is no stator winding with which it can interact. Thus the circuit for this current will possess a high reactance. Any current that will circulate due to this rotational voltage will therefore lag behind the e.m.f. causing it by approximately

90°. This current tends to produce a flux along the dotted line N'-S' at right angles to the main field, and as the currents lag nearly 90° due to the reactance of this circuit it is evident that this second flux will be out of phase, both electrically and in mechanical position, by 90°.

The generated e.m.f. of this circuit is in time phase with the main field, and the rate of change of induced magnetism is equal to that of the generated e.m.f. Therefore the secondary field N'-S' will have a value that is proportional to the rate of change of the current in the conductors A-B, which in turn is propor-

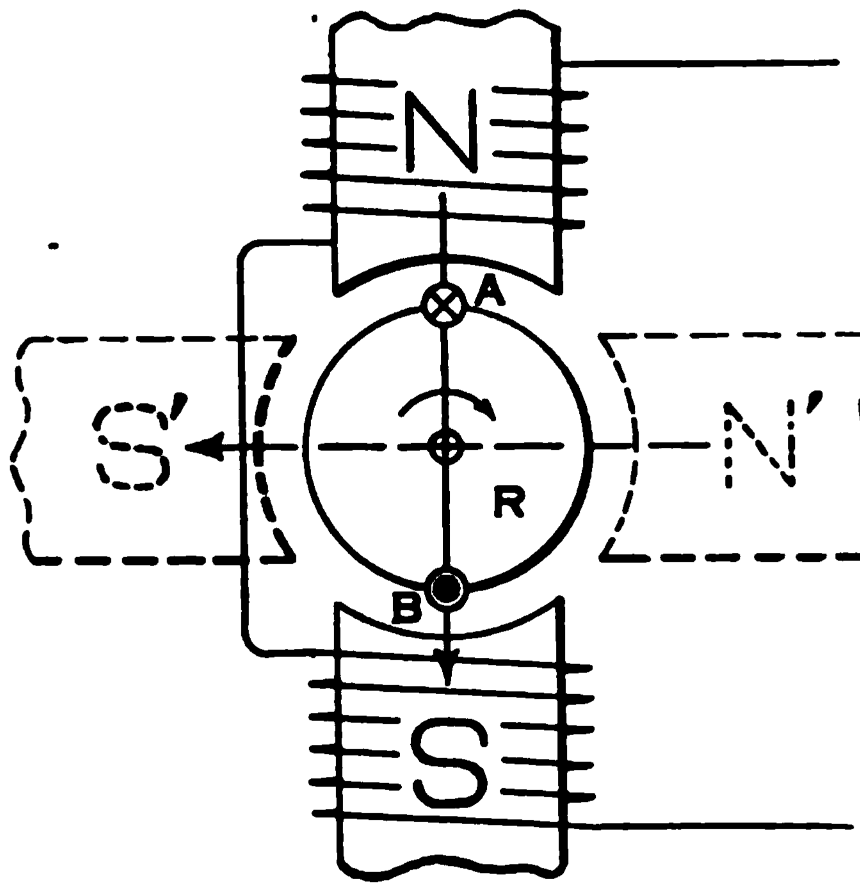


Fig. 844.—Principle of single-phase induction motor.

tional to the e.m.f. induced therein, which in turn is proportional to the rate of change of the main flux.

These two fields will obviously interact to produce a rotary field of force in which the rotor will continue to revolve. For all speeds under synchronism the secondary field will be less in value than the main field, and above synchronism it will be greater. This causes the resultant field to assume an elliptical form, as in Fig. 845, which at synchronism becomes practically circular.

At no load the rotor must carry a sufficient current (magnetizing current plus a small energy component) to produce the induced field. This current must not be confused with the energy current which flows in the rotor when a load is applied.

In general it may be stated that the rotational voltage caused by cutting the main field and the transformer voltage due to the secondary field are nearly 180° out of phase and interact to produce the exciting current of the secondary field. This current does not interact in any way to produce motor torque but produces the secondary flux only and varies with the speed. The voltage generated in the rotor due to the cutting of the secondary field interacts with the transformer voltage due to the main field to produce the working current in the rotor. This current is produced in the same space position with the secondary field with which it interacts to produce the motor torque. While this current and flux are not in time phase, being 90° apart, at synchronous speed, their phase position improves as the motor approaches full-load conditions. The resultant voltage which produces this working current is caused by two components which are nearly 180° out of phase with each other. As one of these varies nearly as the square of the speed, it is evident that

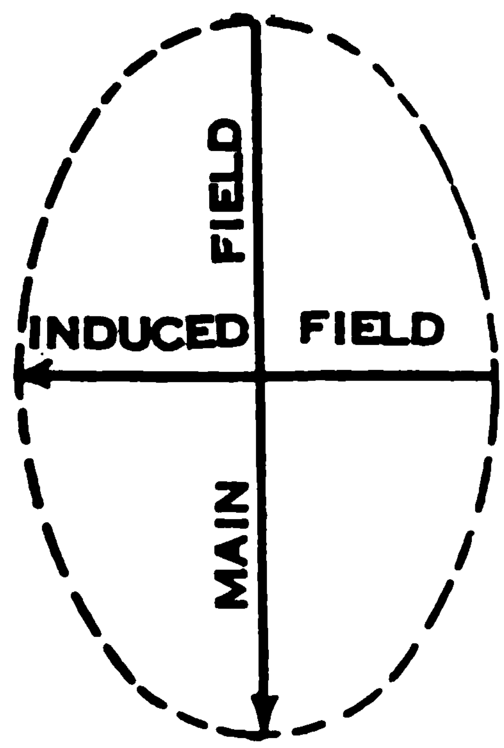


Fig. 845.—Elliptical rotating field in a single-phase induction motor.

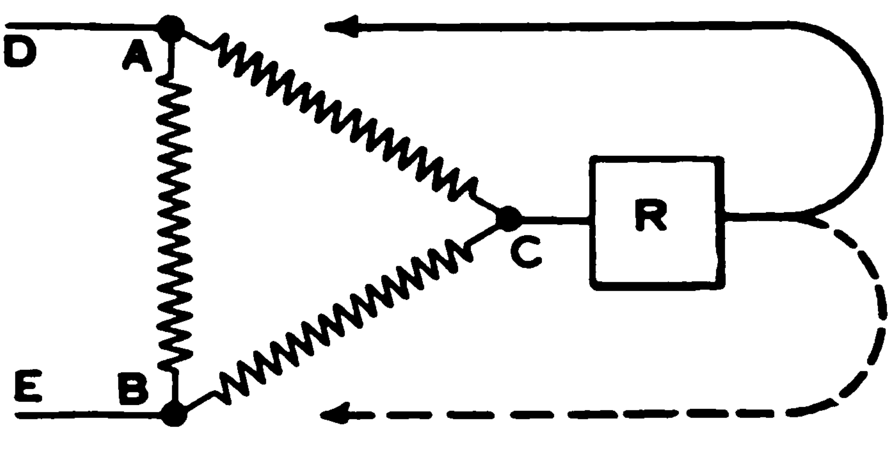


Fig. 846.—Method of starting polyphase induction motor on single-phase circuit by means of resistance in shunt with one phase.

a small decrease in the speed will bring about a considerable increase in resultant voltage and current. This results in a slightly smaller slip in a single-phase than in a polyphase motor of the same rated capacity,

External Phase Splitters for Starting.—Three-phase motors may be operated with reduced output upon single-phase circuits

of the same voltage. Such motors will not start unless provided with means for bringing them up to about 20% of their synchronous speed or unless they are provided with some external phase splitter. The latter is the commonest method. If the stator of a three-phase motor, *A-B-C*, Fig. 846, is connected to a single-phase source, *D-E*, the rotor will not start. If, however, a resistor, *R*, is connected between the points *C* and *A*, a voltage will be impressed upon *A-C* which is out of phase with that on *A-B*. The angle will not be great but will be sufficient to enable the motor to start without load if the resistance of *R* is properly proportioned. The phase displacement so obtained produces a rotating field, somewhat distorted but sufficient to start the motor. As the motor gets up to speed it induces its own rotating field and the resistor *R* may be disconnected. If

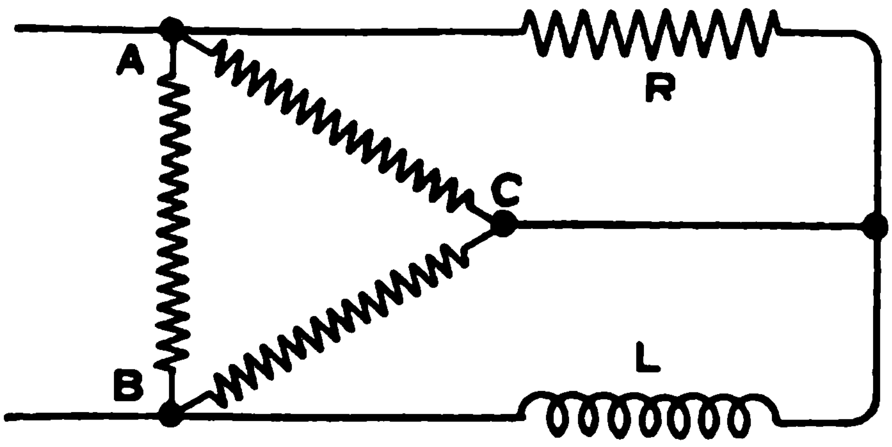


FIG. 847.—Resistance and inductance employed for external phase-splitting to start a three-phase motor on a single-phase circuit.

the wire at *A* is switched to the point *B*, the phase displacement is in the other direction and the field of force rotates in reverse order. The change would cause the motor to start in the opposite direction. External phase splitting may be obtained with a resistor, an inductor or a condenser. A resistance unit is the most readily obtained and is widely used. Inductance is rarely used by itself because the motor circuit is already highly inductive and an additional inductance does not cause much further phase displacement. A condenser would be the best but is comparatively expensive. If, instead of employing resistance alone, a resistor *R* and an inductor *L* be employed, as in Fig. 847, the current is made to lag more in *B-C*, and less in *A-C*, than in *A-B*. The motor would thus start even more readily than when connected as in Fig. 846. External phase splitters of this type are

in no sense starting boxes. They do not reduce the applied voltage but simply bring about a rotating field while the motor takes its customary large starting current.

A method of reducing the voltage on each phase when starting in combination with an external phase splitter is illustrated in Figs. 848 to 850. In Fig. 848 the three phases of the motor stator are connected in Y. Across phases 1 and 2 a resistor, *R*, is connected. Across phases 2 and 3 is a reactor, *L*, while the line voltage is impressed across phases 1 and 3. The phase

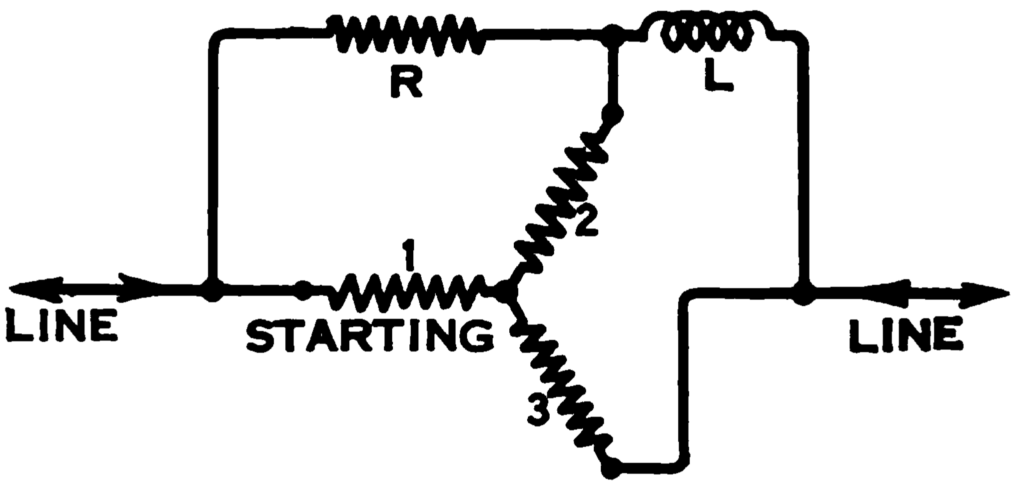


FIG. 848.—Y connection for limiting starting current in an induction motor with external phase-splitting.

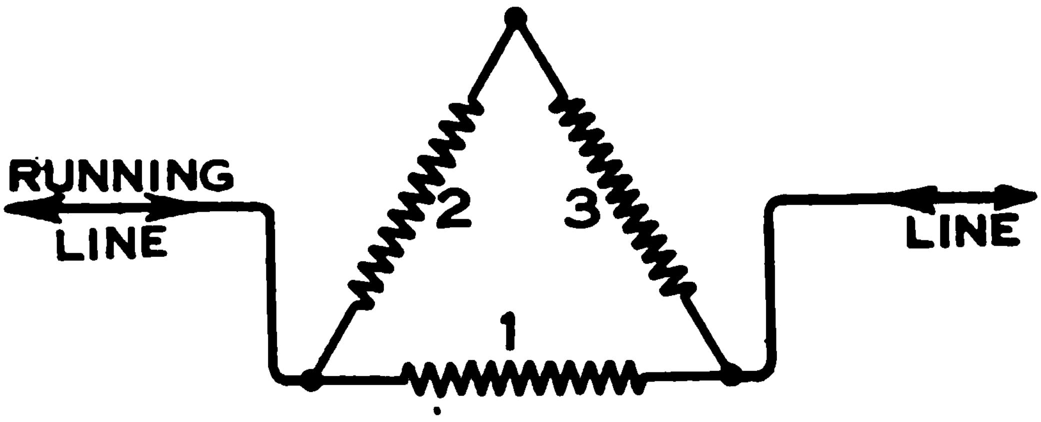


FIG. 849.—Δ connection for running after preceding motor has been started.

displacement obtained by these two devices enables the motor to start quickly. As each phase of the stator is wound for full-line voltage this pressure is reduced nearly one-half on account of the Y connection. When the motor has nearly reached synchronous speed a switch is thrown which changes the connections from Y to Δ as in Fig. 849 and at the same time disconnects the resistor and reactor. The motor then produces its own rotating field and continues to run in the direction in which it was started.

A phase-splitting and connection-changing device used by the General Electric Company for accomplishing the above is illustrated in Fig. 850. It involves a three-blade switch mounted on the top of a box containing the resistor and reactor. The box requires six wires for the two terminals of each phase of the motor *M* which must be led into the box. Tracing the circuit between the line and the motor with the switch in the upper position will show that the connections are established as in Fig. 848. When the switch is thrown to the lower position the connections in Fig. 849 are obtained. To reverse the direction of rotation of such a motor it is only necessary to reverse the connections *A*-*B*—that is, reverse the terminals of the resistor and reactor with respect to the binding screws on the switch on the top of the box.

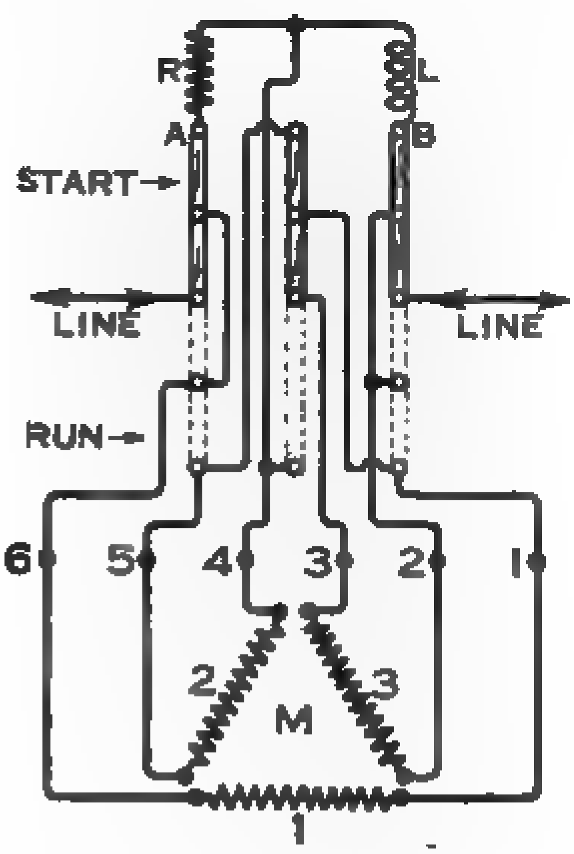


FIG. 850.—Wiring diagram for making connections shown in Fig. 848 and Fig. 849.

Self-Starting Single-Phase Motors.—In the absence of an external phase-splitting device for starting three-phase motors on a single-phase circuit, there are three plans for rendering single-phase motors inherently self-starting. They are: The repulsion method, the condenser method, and the auxiliary winding method.

The Repulsion-Start Type Induction Motor.—This method employs the repulsion principle illustrated diagrammatically in Fig. 851. Here a single-phase alternating current is introduced into a bipolar stator winding in which is located an armature with a winding like that on a direct-current machine and provided with a commutator. On this commutator are a pair of brushes disposed at an angle with respect to the normal position for direct-current brushes and short circuited on themselves. When single-phase alternating current is introduced into the stator winding the armature rotates because of a repulsion which sets

in between closely approaching poles of like sign on the rotor and stator.

To understand the way in which the rotor currents are produced, consider Fig. 852. Here the brushes are placed in what would correspond to the neutral position in a direct-current machine and are short circuited. If an alternating flux be

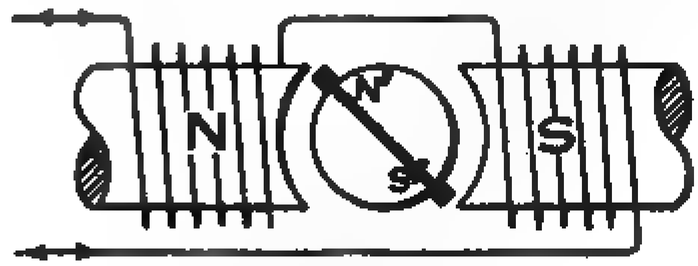


Fig. 851.—General plan of single-phase repulsion-induction motor.

projected through the armature in the direction N-S, an induced e.m.f. would be set up in the upper and lower branches of the winding which, according to Lenz's Law, would oppose this flux. A Gramme ring winding is shown, although the actual construction consists of a drum winding. Assuming the armature to be motionless, the induced e.m.f. will be as in a trans-

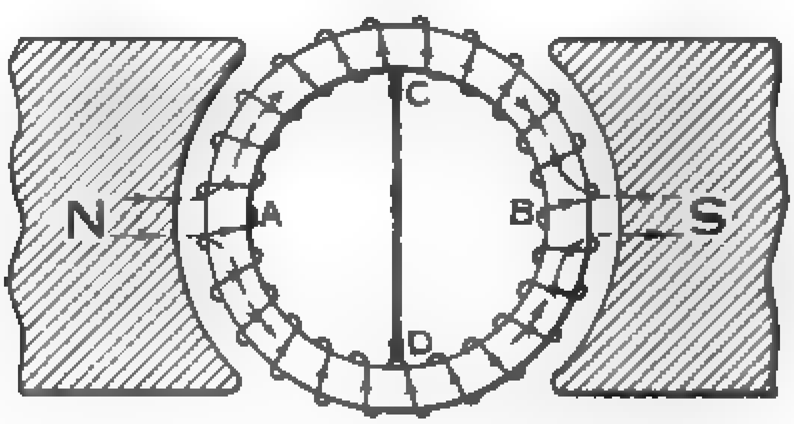


Fig. 852.—With short-circuited brushes in position shown, no current will be induced in armature winding.

former, and the armature winding will act as a secondary with respect to the flux supplied by the stator primary. Examining the induced e.m.fs. which will occur at the instant pictured, it will be observed that an e.m.f. will be produced which will tend to urge a current from C to A and from D to A, the e.m.fs. in these two circuits being equal and opposite to each other, no current will result. For similar reasons the e.m.f. from B to C opposes

that from B to D, and no current will be produced between the short-circuited brushes at C-D. Should the brushes be turned through an angle of 90° to the position shown in Fig. 853, the induced e.m.fs. between B-C-A will now be all in one direction and those between B-D-A likewise in the same direction. These e.m.fs. will combine at the proper point, A, to produce two currents in parallel, which will flow through the short circuit from A to B, developing a magneto-motive-force in the direction N'-S', diametrically opposed to the main flux N-S. The armature poles being on dead center with respect to the stator poles, no torque can result. If, however, the brushes are placed at some intermediate position between that shown in Fig. 852,

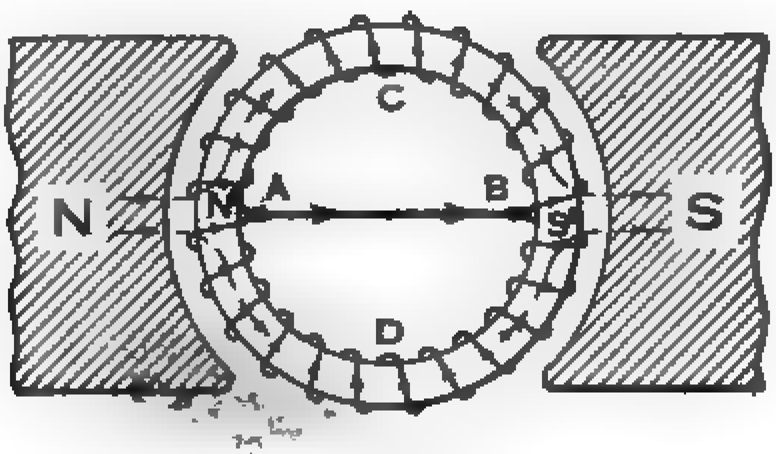


FIG. 853.—With short-circuited brushes in position shown, currents will be induced but no torque will be developed by the armature.

where there is no current, and Fig. 853, where there is no torque, it is evident that there will be some current induced and some torque. Such a condition is illustrated in Fig. 851. Repulsion ensuing between N and N' and between S and S', the **rotor travels in the direction of the brush displacement from the stator poles.** Should the brushes be shifted anti-clockwise instead of clockwise from the plane of main flux, N-S, rotation would ensue in the reverse direction. Such a motor starts with a large torque, very much superior to that of an ordinary induction motor. Sparking, however, would prevent the brushes being left in this position permanently. Therefore, when the motor has been brought up to speed, a centrifugally operated lever is made to remove the brushes from the commutator and at the same time throw a short-circuiting ring around the commutator which connects all the segments together and converts

the winding into the equivalent of a squirrel-cage rotor. Thereafter the motor continues to run as a single-phase induction motor. If loaded below a certain point, the brushes automatically come on the commutator and the short-circuiting ring is removed from the segments and the motor operates on the repulsion principle, with its correspondingly large torque. The carrying capacity of its winding would not permit its being

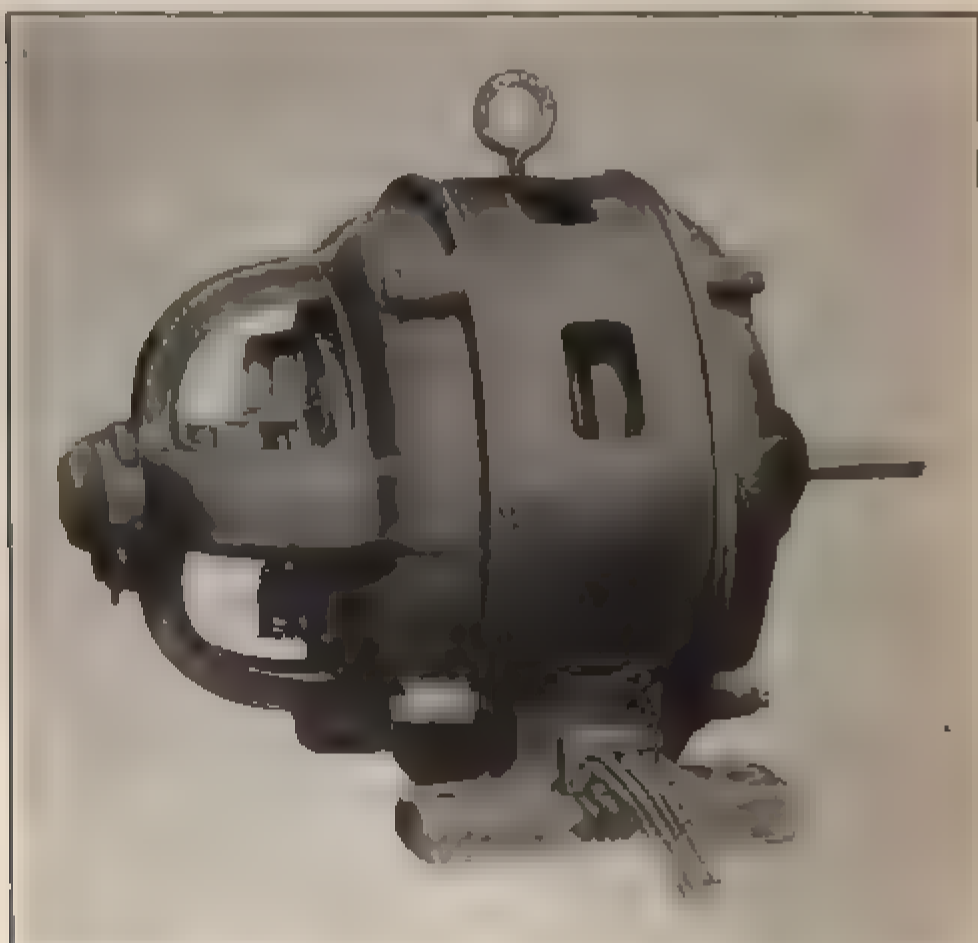


FIG. 854. Westinghouse 10 h.p. type A. R. single phase repulsion start induction motor. The commutator is short-circuited by centrifugal force after the motor has been brought up to speed.

operated permanently, however, with the brushes on the commutator. Fig. 854 illustrates a 10-horse power Westinghouse type *A-R* motor operating on this principle.

A plan has been devised for compensating the repulsion motor which improves commutation so as to obviate the necessity for removing the brushes and short-circuiting the commutator and at the same time raises the power factor at full load to practically 100%. Two general plans of compensating such a motor are in use. Fig. 855 represents the **series compensated** type and Fig

856 the **inductively compensated** motor. In Fig. 857 an e.m.f., *E*, is impressed upon the stator winding and a pair of auxiliary brushes *A-A* connecting the armature in series with the stator winding. At right angles thereto are the energy brushes, *B-B*,

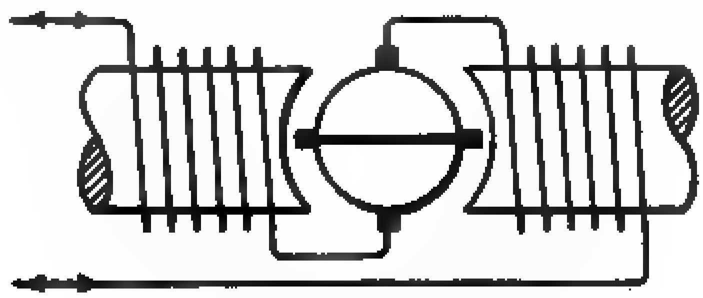


Fig. 855.—Series-compensated repulsion-induction motor.

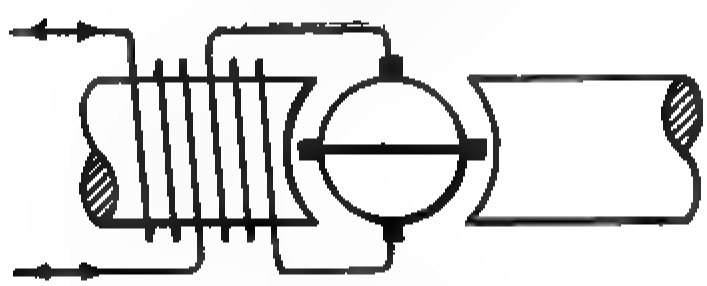


Fig. 856.—Inductively compensated repulsion-induction motor.

on short circuit. By a transformer action the stator winding, acting as a primary, induces in the stationary armature a secondary current which passes through the short circuit from *B* to *B* the same as in Fig. 853. The reaction of this secondary current

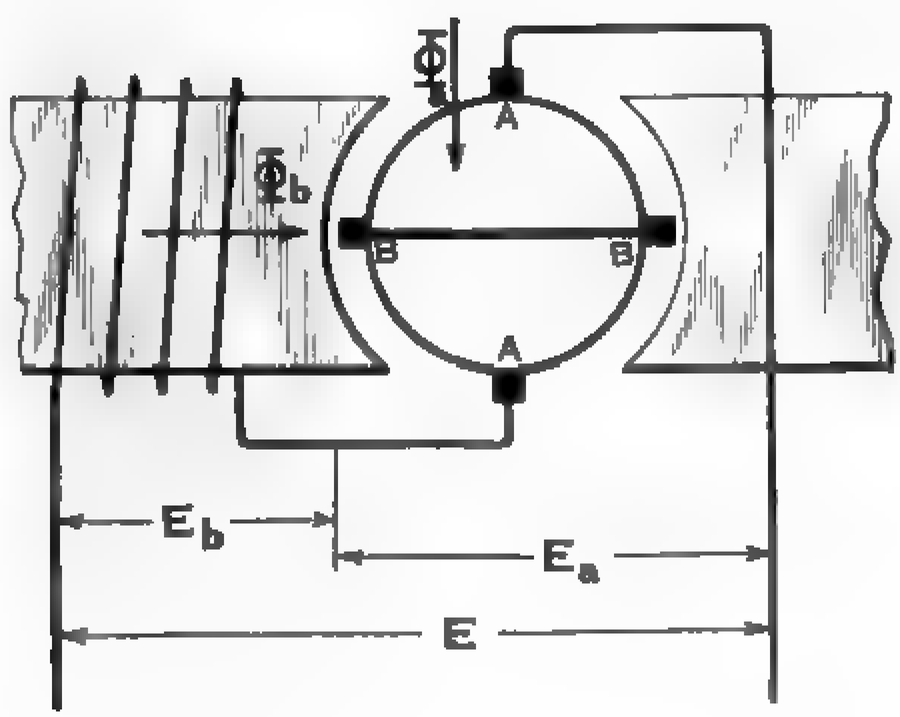


Fig. 857.—Various voltages and fluxes involved in series-compensated repulsion-induction motor.

opposing the primary flux practically neutralizes the self-induction of the stator winding so that the drop E_b is merely due to resistance, while the drop E_a is practically wholly inductive. Thus the line drop, E, Fig. 858, is separated into two components, A-B, due to the stator winding, and B-C, due to the armature winding. The current led conductively through the armature, A-A, produces a secondary flux Φa in the direction shown. The interaction of the current in B-B and the flux in Φa produces a resultant flux displaced mechanically from the main flux Φb and torque ensues. When the armature revolves, two rotational e.m.fs. are generated, one appearing at A-A due to cutting of the primary flux Φb, which opposes the inductive drop across the armature, A-A. The voltage E_a is thus reduced and the applied voltage E being constant, the drop across the stator E_b rises. The rotation of the armature also generates another voltage across the brushes B-B due to cutting of the flux Φa. This is in opposition to the former flow of current across B-B due to trans-

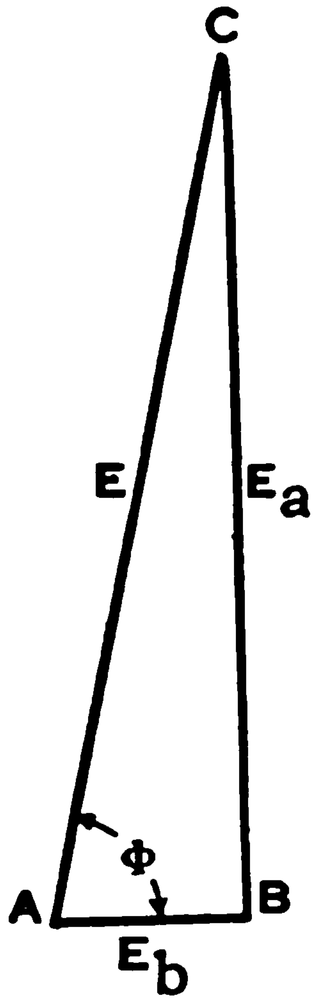


FIG. 858.

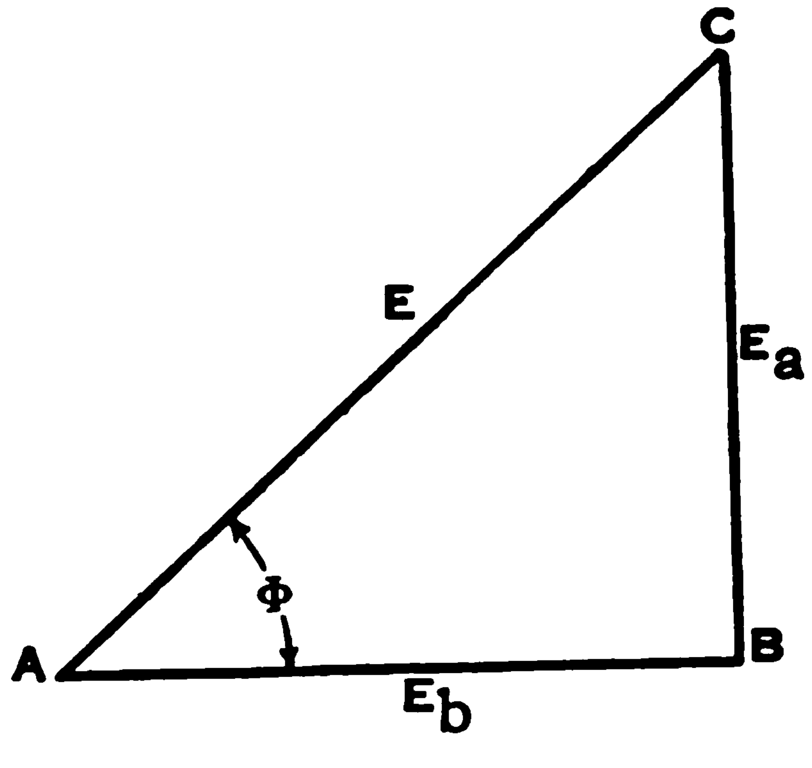


FIG. 859.

former action therein. As the secondary current through B-B due to transformer action falls, its tendency to neutralize the stator's self-induction lessens and the drop E_b increases in proportion to the speed. Fig. 859 shows how the drop A-B rises

and the drop *B-C* falls. When the motor reaches synchronism the drop E_a across the armature is very small, and the drop E_b is practically the entire line voltage. This is represented in Fig. 860. The power factor is then nearly 100%.

If the number of turns in the armature and stator are equal, the motor will operate at 100% power factor at synchronous speed. If the auxiliary brushes *A-A* are supplied by an induced current derived from a series transformer or from a separate winding surrounding the stator poles, as shown in Fig. 856, the current impressed may be made anything desired, depending on the ratio of transformation. By varying the ratio, the motor may be compensated to operate at 100% power factor at any desired speed.

An unusual form of repulsion motor is built by the Wagner Company. Two windings are used on the rotor. In the bottom of the slots is placed an ordinary squirrel-cage winding. This

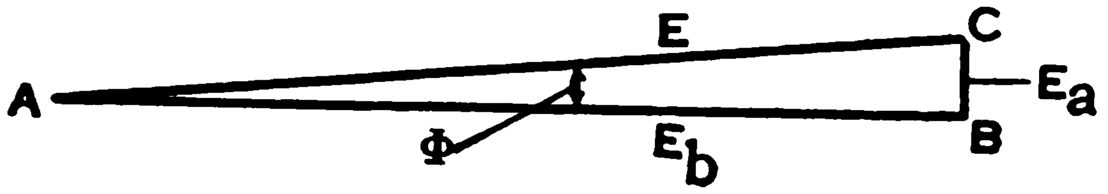


FIG. 860.

is covered by a magnetic separator of soft iron. In the top of the slot is placed the usual formed coil winding which connects to the commutator. On the commutator are placed four brushes. The first set are in series with the stator winding, and across the latter brushes the compensating winding is placed in the circuit after the motor reaches speed. The compensating winding is placed in slots in the stator, and the amount required is experimentally determined. The performance of the motor is similar to that of any other compensated repulsion motor with the exception that the tendency, which is characteristic of a series-wound motor, to race at light load is checked by the squirrel-cage winding which causes it to run more like a shunt-wound motor, that is, at a constant speed.

Condenser-Start Type Induction Motor.—Motors may be started and operated upon single-phase circuits without a commutator by employing a three-phase stator winding as shown in Fig. 861, and squirrel-cage rotor. Single-phase currents are admitted at the points *A-B*. A condenser, *K*, is connected

across a portion of the main winding *B-C*. This condenser is of sufficient capacity to supply this section with its proper current differing in phase by a considerable angle from that admitted to *A-B*. Connected as shown, the condenser is smaller and less troublesome than when connected across the main terminals of the motor. The machine now becomes self-starting on single-phase circuits and operates with a high power factor. In large sizes a power factor of 100% is often obtained. The condenser is mounted in an hermetically sealed brass case and placed in a cast-iron base under the motor. It may be left in circuit permanently. If desired, the rotor may be of the coil-wound type with an internally placed starting box which is cut out automatically by a centrifugal switch when the motor reaches full speed. A friction clutch pulley is desirable to allow the motor to start without load.

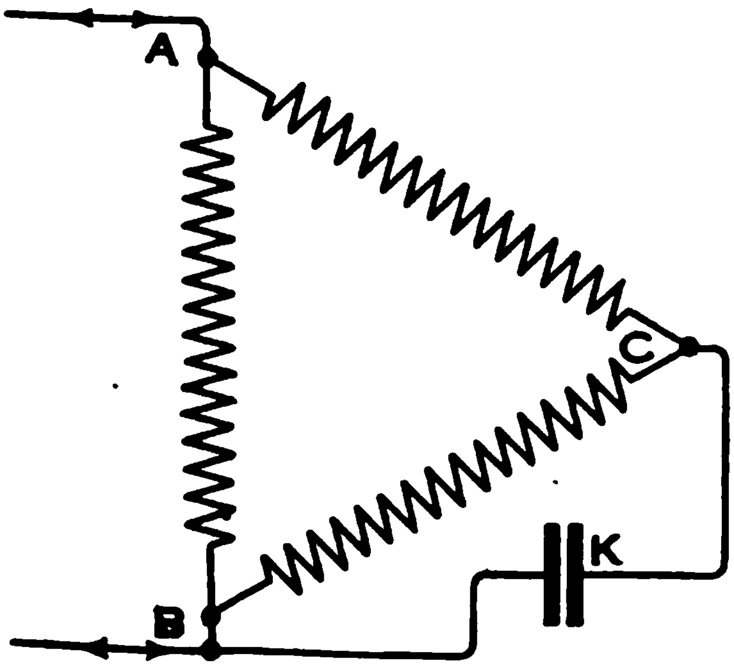


FIG. 861.—Position of condenser for splitting the phase to make a polyphase induction motor self-starting on a single-phase source.

Auxiliary Winding Type of Induction Motor.—Another and less expensive type of single-phase motor is one that divides the winding into two parallel paths, as shown in Fig. 862. Winding *A* is of high resistance and small inductance. The impedance of this is illustrated at *A*, Fig. 863. The winding *B* is of high inductance and low resistance. The impedance for this winding is illustrated at *B*, Fig. 863. These two windings are displaced mechanically from each other by about 90°. On account of the difference in their design, the currents in the two windings are made to differ by a considerable angle, Φ, Fig. 863. A rotating field is thus set up which interacts with the cage winding on the rotor. When the motor has once started, the auxiliary winding

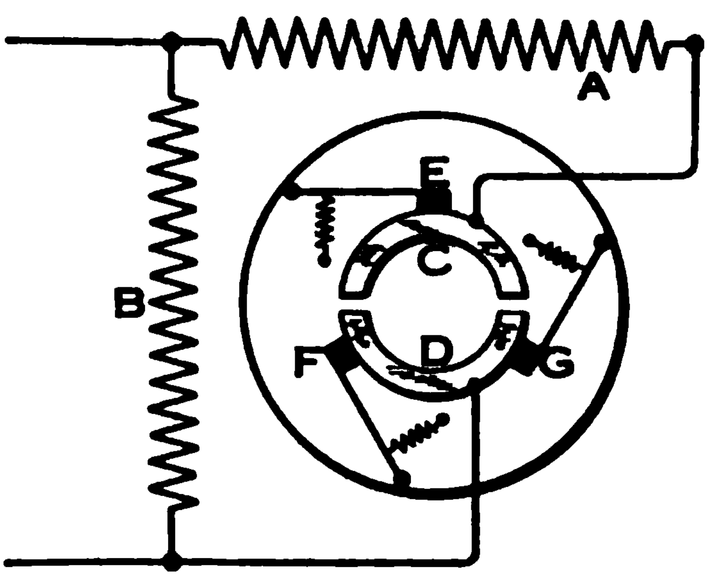


FIG. 862.—Centrifugal switch for disconnecting auxiliary winding of split-phase motor after starting.

A is no longer necessary and may be cut out. This is done by means of an automatic switch. In the end of the stator are two stationary segments or half circles, C-D, Fig. 862. On these rest three brushes, E-F-G. The three brushes are all connected together and attached to, and rotate with, the rotor. The two segments, C-D, are thus connected with each other, and the winding A is in parallel with the winding B across the source of supply. When the motor approaches synchronism, the three brushes are thrown off the segments by centrifugal force and the winding A is cut out. The motor then continues to run as a pure single-phase machine. The disconnecting of the auxiliary winding effects an economy, as the power absorbed by that winding is not necessary for its continuous operation. To reverse the direction of such a motor the terminal connections of either the winding A or B must be reversed.

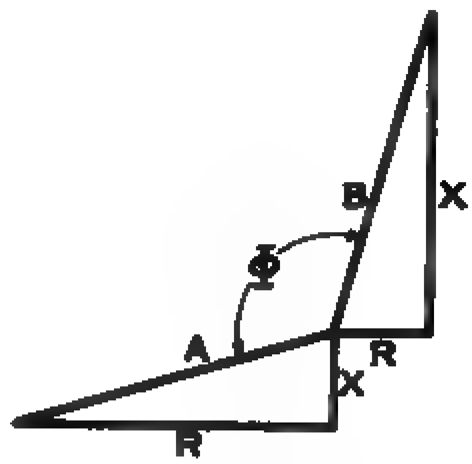


FIG. 863.

Shading-Coil Type of Induction Motor.—An ingenious type of single-phase induction motor which has a definite direction of rotation employs the **shading coil,** Fig 864. The main field winding, M, is supplied with a single-phase alternating current through the lines A-B. An alternating flux is established by this winding through the rotor in the direction, C, shown. If at a given instant this flux is downward, there will be induced by the rotor a counter magnetomotive-force upward in the opposite direction, N. The main pole is separated into two portions. Upon one of these sections a small, bare copper short-circuited winding B is placed. This coil is subjected to the same main flux as the rotor. The secondary current in the shading coil rises in phase with the secondary current in the

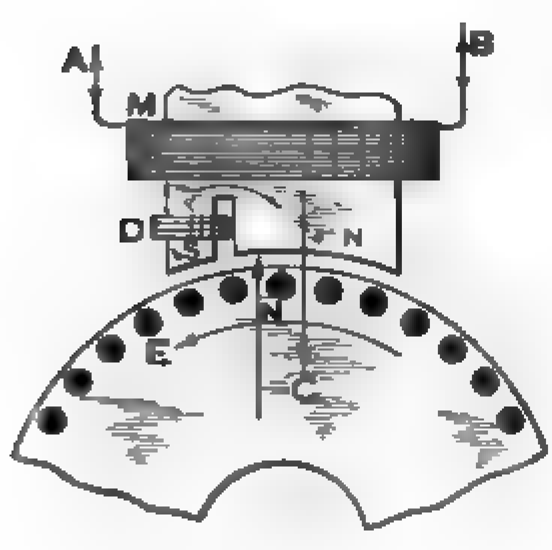


FIG. 864.—Principle of shading-coil self-starting induction motor.

rotor. The shading coil, however, is off dead center with respect to the main flux, while the secondary current in the rotor is symmetrical with respect to the main field poles. Thus, when these two secondary currents rise in the same time phase, they are relatively displaced mechanically in position. The shading coil tends to produce poles *s-n*, as shown. The rotor tends to produce a north pole *N* as shown. The rotor's *N* pole is thus repelled from *n* and attracted by *s*, and moves toward the shading coil in the direction *E*.

In larger machines the shading coils are wound with insulated wire and all such coils connected in series. An automatic centrifugal switch could then be provided to cut the shading coils out of circuit at full speed. For fan motors these machines are provided with four main stator poles and four shading coils, each of the latter being individually short circuited upon itself as shown.

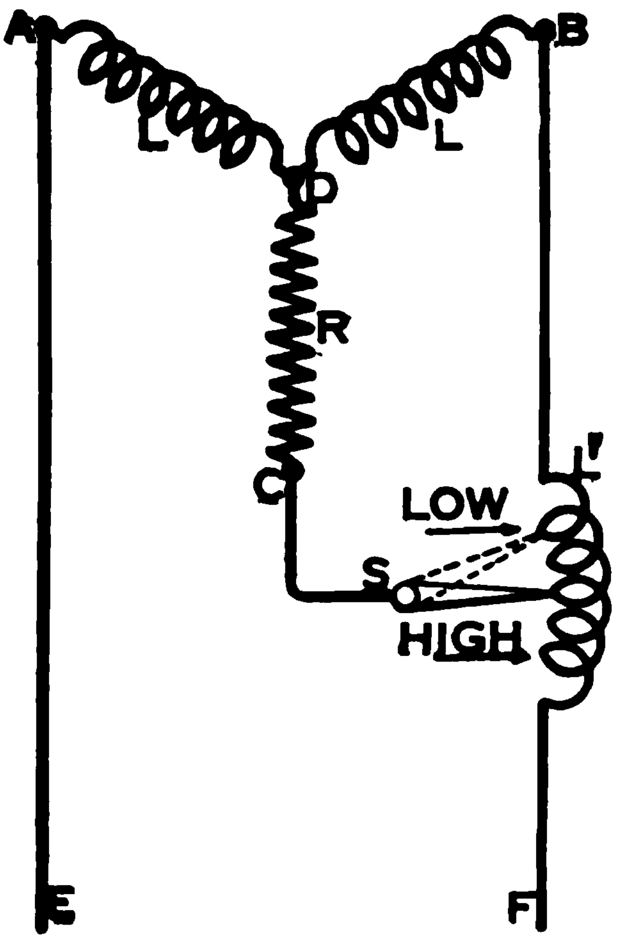


FIG. 865.—Scheme commonly employed for single-phase, self-starting, variable-speed, induction-type fan motors.

The objection to the small shading coil motor was that it ran only in one direction, a reversal being impossible without placing the shading coil on the other pole tip. Furthermore, it left the shading coil in the circuit continuously, thus involving a certain amount of lost power after the motor was started.

Later Types of A. C. Fan Motors.—The majority of alternating-current fan motors are now provided with a distributed winding resembling that of a three-phase machine, Fig. 865. Two of these windings, *A-D* and *B-D*, are highly inductive, while a third, *D-C*, is of high resistance. The single-phase source supplies current from the mains *E-F* to the points *A-B*. In series with the line *F-B* there is connected a small adjustable reactance, *L'*, located in the base of the motor. By means of a commutating switch *S*, the phases *A-D* and *D-C* are placed directly across the line, while the inductance *L'* is connected in series with phase

B-D, thereby causing a maximum displacement of current in this phase when the highest speed is obtained; or the inductance L' may be shifted until it is in series with the entire motor, when the lowest speed would be obtained. Such motors are invariably provided with cage-wound rotors.

Small single-phase commutating fan motors have been designed which are similar to direct-current motors—that is, they are provided with a direct-current armature and commutator and their fields are connected in series with the armature. A direct-current motor would run on an alternating circuit provided the field structure was laminated to prevent the induction of eddy currents therein. It would be necessary, however, to also reduce the number of convolutions in the field to avoid the high self-induction which would be encountered. When these pre-

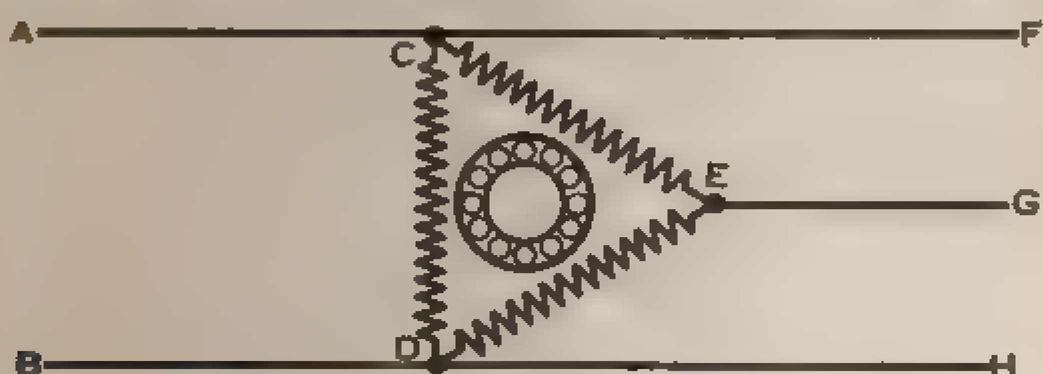


FIG. 866.—Single-phase motor used as a source of three-phase currents while operating on a single phase supply

cautions are taken the motor will run on alternating as well as direct current. It is often termed a **universal motor.** Such motors have been built in large sizes and are used for railroad work, of which the most conspicuous example is the type used in connection with the electrification of the New York, New Haven and Hartford Railroad. There the field reactance is reduced by operating the motor on low frequency as well as by reducing the number of convolutions in the field winding. The magnetic reluctance is made low by using a very small air gap. The inductance of the armature is decreased by the use of a compensating winding which neutralizes the magneto-motive-force of the armature and reduces the flux which the armature itself tends to produce. The field frame is well laminated and the flux density employed quite low. These features in design make the series motor for A.C. circuits heavier and more costly than for direct-current motors of the same type and horse power.

Phase Converter.—A single-phase source may be made to deliver three-phase currents through the medium of a three-phase induction motor. If in Fig. 866 the phase *C-D* of such a motor is connected to a single-phase source, *A-B*, and the cage-wound rotor is started mechanically or by some phase-splitting arrangement, it will continue to run as already explained. Being a pure single-phase machine it will set up its own rotating field and the currents induced in the rotor from *C-D* will, in their reaction, induce currents back into the stator sections *C-E* and *E-D*, each of which is out of phase with the other and both out of phase with *C-D*. From the points *F-G-H* three alternating currents differing in phase and varying symmetrically may be obtained. This is the basis of the design of the phase converter employed on the Norfolk and Western electric locomotives for converting the single-phase supply into polyphase currents for operation of induction motors therein.

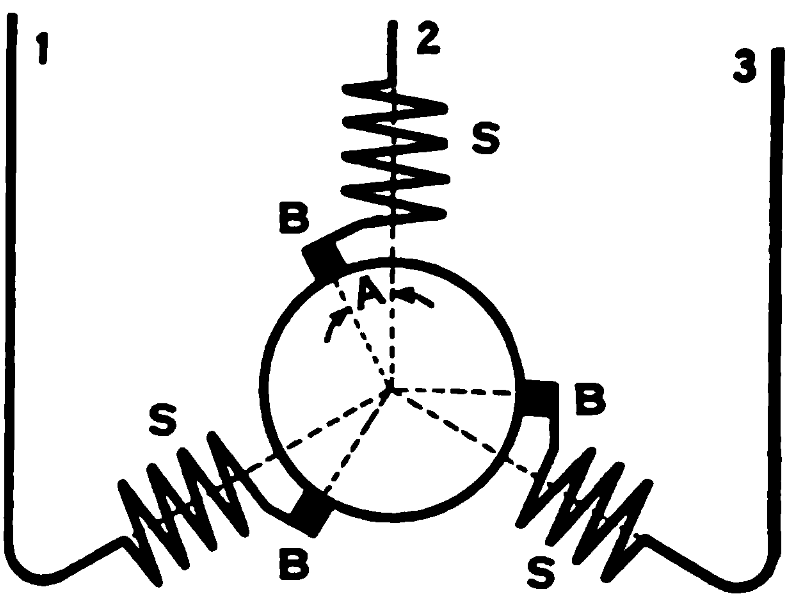


FIG. 867.—Electrical circuits of three-phase variable-speed commutator motor built by the General Electric Company.

Polyphase Series Motors.—The General Electric Company manufactures a polyphase series motor in which speed control is obtained through a wide range merely through shifting the position of the brushes. For certain classes of work such as the operation of centrifugal fans, centrifugal pumps and cloth-printing presses, this motor possesses some novel and desirable features. The motor was originally developed in Germany and has been operated successfully abroad for several years. In its performance it resembles the series direct-current motor, but has the advantages of requiring no separate controlling device and of operating at a high power factor and efficiency. The motor consists essentially of a three-phase distributed winding placed in a stator identical with that commonly used for a standard polyphase induction motor. It has a standard direct-current armature with a commutator. The arrangement of the windings is shown diagrammatically in Fig. 867. For commercial voltages the current passes through a three-pole single-throw disconnecting switch and thence through

the three stator windings. The three brushes, *B-B-B*, are either supplied directly from the line as shown or with separate currents supplied from the secondaries of series transformers Y connected. The latter plan is often of advantage in enabling a reduction of potential to about 80 or 90 volts which is delivered to the brushes

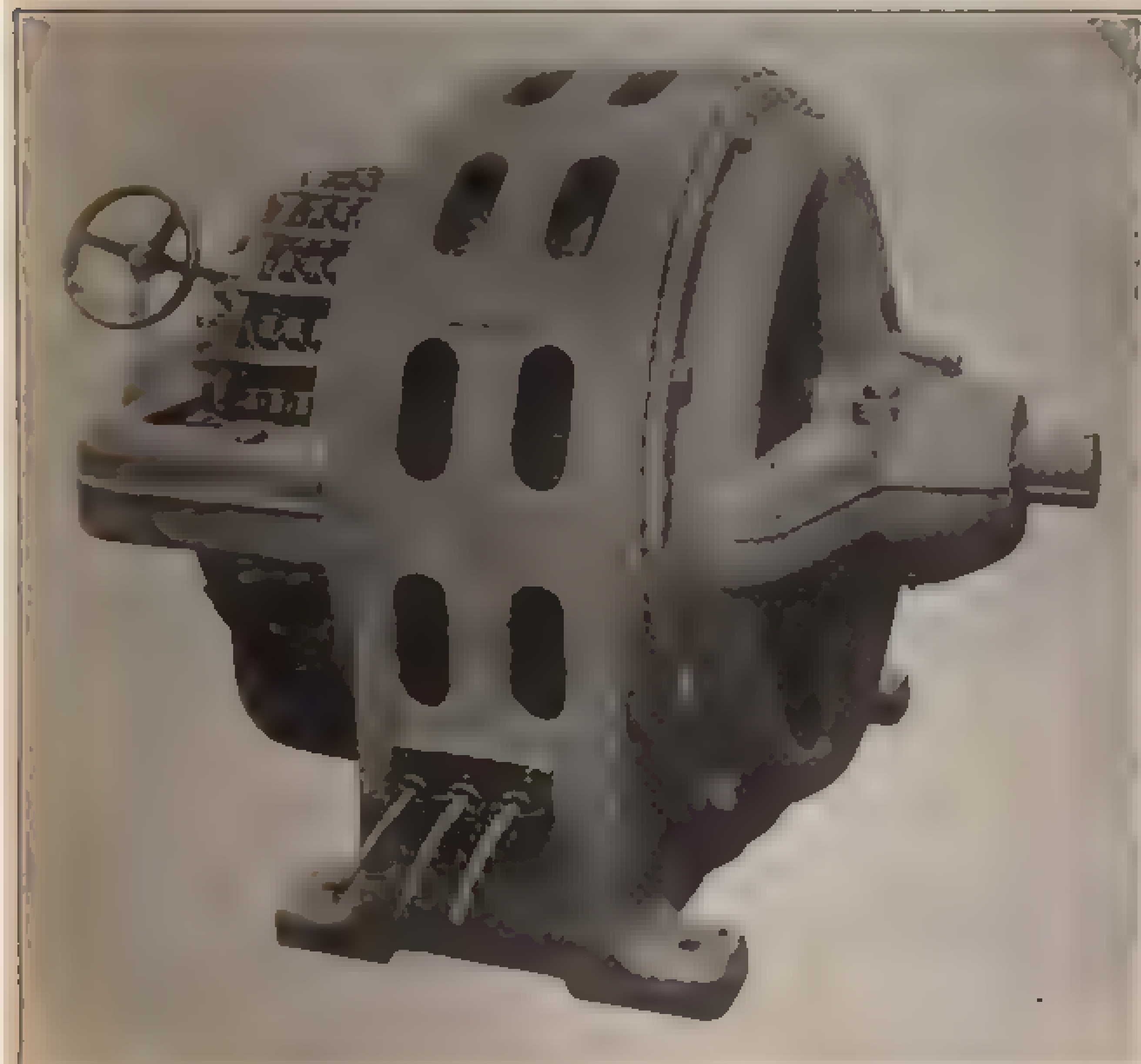


FIG. 868.—General Electric three-phase 100-H. P., 440-volt, brush-shifting variable-speed motor.

and insures better commutation. The most striking feature of this machine is the entire absence of any external starting or speed-control device. The motor is started, accelerated, stopped and reversed by shifting the brushes. With the brushes in the same axis as the stator winding, no field is produced by the line current, for the ampere turns of the rotor are equal in amount and opposite in direction to those on the stator. If the brushes

are shifted through an angle A, the balance between rotor and stator windings no longer exists and the resultant ampere-turns produce an excitation proportional to the current in both windings and to the angle of brush shift. The motor will now develop a torque which is proportional to the square of the line current and the angle of brush shift. If the brushes are shifted gradually backward, the line current and motor torque increase slowly until the motor comes up to a speed depending on the load. Commutation is sparkless from about 10% above synchronism to 70% below synchronism. These motors have been operated successfully in sizes up to 100 horse power. Fig. 868 shows the appearance of a complete 440-volt brush shifting motor of this type, the hand wheel being employed for starting and adjusting of speed.

The various types of alternating current motors available and the kind of work for which they are adapted may be briefly summarized as follows:

1. **Synchronous Polyphase Motors.**—Self-starting only as induction motors; require an exciter; cannot be changed in speed; employed usually in sizes above 100 horse power only; high power factor.

2. **Polyphase Induction Motors.**—Self-starting; adapted for all classes of work; comparatively low-power factor; available with three types of rotors; squirrel-cage type, rugged, practically indestructible, with low starting torque and low power factor; internal resistance type improved starting torque and better power factor; slip-ring type, greater flexibility in starting and operating; employing minimum current under all conditions; may be operated on single-phase circuits by use of external phase splitters.

3. **Repulsion Motor.**—Employs commutator and brushes; a very satisfactory single-phase motor in sizes up to 20 horse power; high starting torque and, when compensated, operates at high power factor.

4. **The Auxiliary Winding Type.**—Has a main winding and an auxiliary winding, the latter having a high resistance which is cut out by a centrifugal switch at slightly below synchronous speed; low starting torque and power factor.

5. **The Condenser Type.**—A single-phase self-starting motor with a condenser for splitting the phase; condenser permanently in circuit; small starting torque; operates at high power factor and is high in first cost.

6. **Shading coil** and other split-phase types for fan motors and other very small work only.

7. **Universal Motors.**—Series wound, with laminated field structure; similar to direct-current machines, having armatures, commutators and brushes; operate on both A.C. and D.C. Have characteristics of series direct-current motor. Used considerably in very small sizes for fans, vacuum cleaners, buffing machines, and in very large sizes for railway work.

8. **Brush Shifting Motor.**—Polyphase series wound, with commutator and brushes; started, stopped, reversed and adjusted in speed throughout entire range by shifting of brushes.

SECTION XVI CHAPTER IV

ALTERNATING-CURRENT MOTORS

PRINCIPLES OF INDUCTION MOTORS

1. Explain how the rotating field of force is induced in the pure single-phase induction motor.

2. Explain how a three-phase induction motor may be made self-starting on a single-phase circuit by the aid of an external phase splitter.

3. What are the relative advantages of resistance, reactance and capacity or combinations thereof, for externally splitting the phase when starting a polyphase induction motor on a single-phase circuit?

4. With an external phase splitter, what is the advantage of starting such a motor in Y and running it in Δ ?

5. Explain the fundamental principle in the "repulsion-start" type of induction motor.

6. What is the starting torque and general characteristic of the repulsion-start induction motor. What are its advantages and disadvantages?

7. Explain the advantages of the "series-compensated" and "inductively-compensated" repulsion induction motors.

8. Explain the principle and advantages of the "condenser method" of starting an induction motor on a single-phase circuit.

9. Explain the construction and advantages of the "auxiliary-winding" type of induction motor.

10. Explain the principle of construction, advantages and disadvantages of the "shading coil" type of induction motor.

11. Explain the general plan of modern self-starting, adjustable speed, induction fan motors.

12. Explain the construction of the "universal" motor for use on either A. C. or D. C. circuits.

13. Explain the principle by which an induction motor may be used as a "phase converter." Sketch.

14. Explain the principle of construction of the three-phase, series, commutating, adjustable speed, brush shifting motor.

A. C. MOTORS

PRINCIPLES OF INDUCTION MOTORS

Induction Motor Winding

The winding of an induction motor stator as a whole is divided up into sections called **phase poles.** This is a group of coils connected in series and constituting the polar group for one phase. The number of coils for each phase pole is found by dividing the total number of coils by the product of the number of poles in the motor and the number of phases. Fig. 869 represents the layout for a stator winding having 24 slots, each containing two half-coils or an average of one coil per slot. The spread of the coils is such as to develop four polar regions, each coil occupying a space represented by the distance between 1 and 2—that is, the two halves of one coil occupy slots one and six. As the full polar span would be represented by slots one and seven, this is a "fractional pitch" winding. A "phase-pole" for this machine will therefore consist of

$$\frac{24 \text{ coils}}{3 \text{ phases} \times 4 \text{ poles}} = 2 \text{ coils per phase per pole.}$$

That is, a phase pole would consist of two coils.

A four-pole induction motor would have a synchronous speed of 1,800 r.p.m. If such a machine were required for a three-phase circuit, the usual number of coils would then be:

3 phases $\times$ 4 poles $\times$ 2 coils per phase per pole = 24 coils,
or 3 phases $\times$ 4 poles $\times$ 3 coils per phase per pole = 36 coils,
or 3 phases $\times$ 4 poles $\times$ 4 coils per phase per pole = 48 coils,
or 3 phases $\times$ 4 poles $\times$ 6 coils per phase per pole = 72 coils.

Thus for a fixed number of phases and speed the motor must have a definite number of coils.

Induction motor windings for four-pole machines are frequently designed so that if it is desired to operate the motor on a 110-volt source, all the phase-pole groups for each phase are connected in parallel. If it is to be used on 220 volts, two phase-pole groups are connected in series and this combination connected in parallel

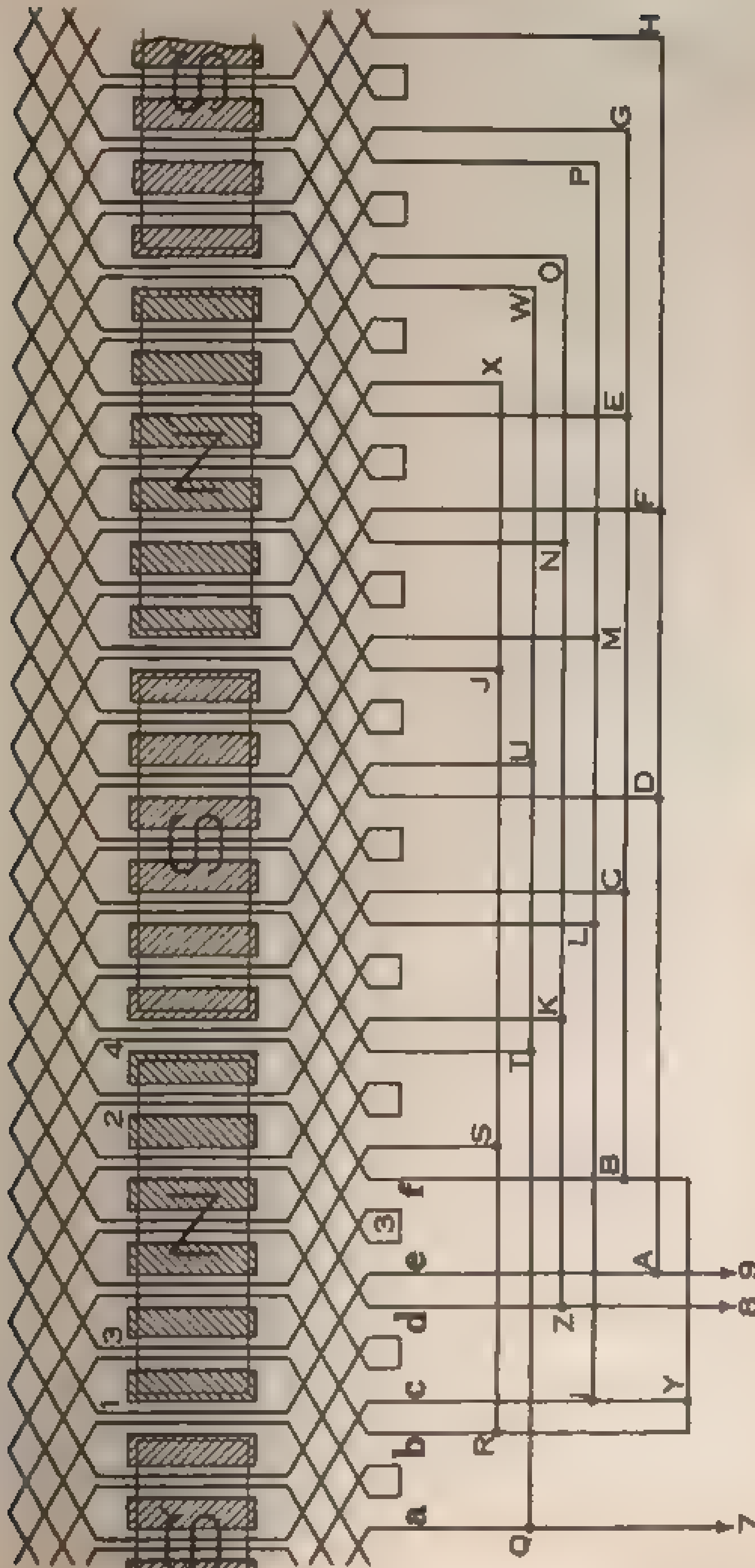


FIG. 869.—Stator winding for induction motor connected four-parallel star for 110 volts.

with a similar group of the same phase. If the motor is to be used on 440 volts, four phase-pole groups are connected in series. If the motor is designed with more than four poles the combinations are correspondingly varied. Windings of this character are designated as four-parallel-star, two-parallel-star, series-star or four-parallel-Δ, etc., the number indicating the number of parallel paths in each phase. In all cases it is of course necessary that the proper polarity be preserved in the connection of the coils. The voltage per turn is the same in all cases.

In Fig. 869, conductors 1, of the first coil, will occupy the upper half of the first slot, and conductors 2 of the same coil will occupy the bottom half of another slot, these two slots being separated by the pitch of the winding. The terminal of this coil joins at 3 with the first end of another coil occupying positions 3 and 4. These two coils, in series terminating at *e* and *f*, constitute a phase pole. Similarly *a-b* and *c-d* represent the terminals of the other two sets of phase poles. Now the group *e-f* is connected at the points *A-B* in parallel with the corresponding group in front of the other north pole *N'* at the point *F-E*. The corresponding groups in front of the two south poles are likewise connected in parallel, but as the windings surround poles of reversed sign the connections *C-D* and *G-H* are reversed with respect to those surrounding north poles. In a similar manner the phase pole terminals *c-d* are paralleled at *I-Z* with the corresponding group in front of the other pole of the same sign at *M-N*, while the corresponding coils surrounding the two south poles are paralleled with reversed connections at *K-L* and *O-P*. The terminals of the phase pole *a-b* are paralleled at *Q-R* with a similar set at *U-J*, while the corresponding connections from opposite poles are paralleled with these two but with reversed connections at *S-T* and *X-W*. In a certain motor the windings so connected are adapted for a 110-volt circuit when the three separate phases are connected in Y. This is done by connecting the points *R-I*

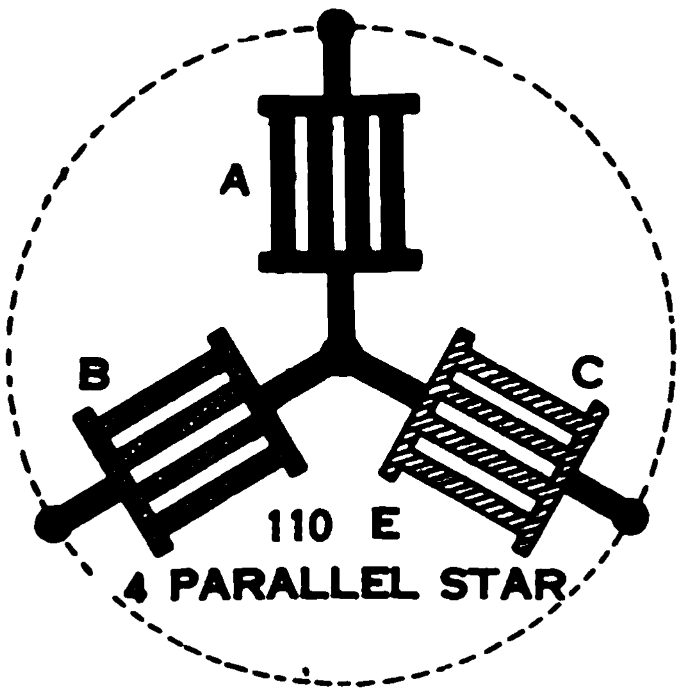


FIG. 870.—Relative position of parallel circuits.

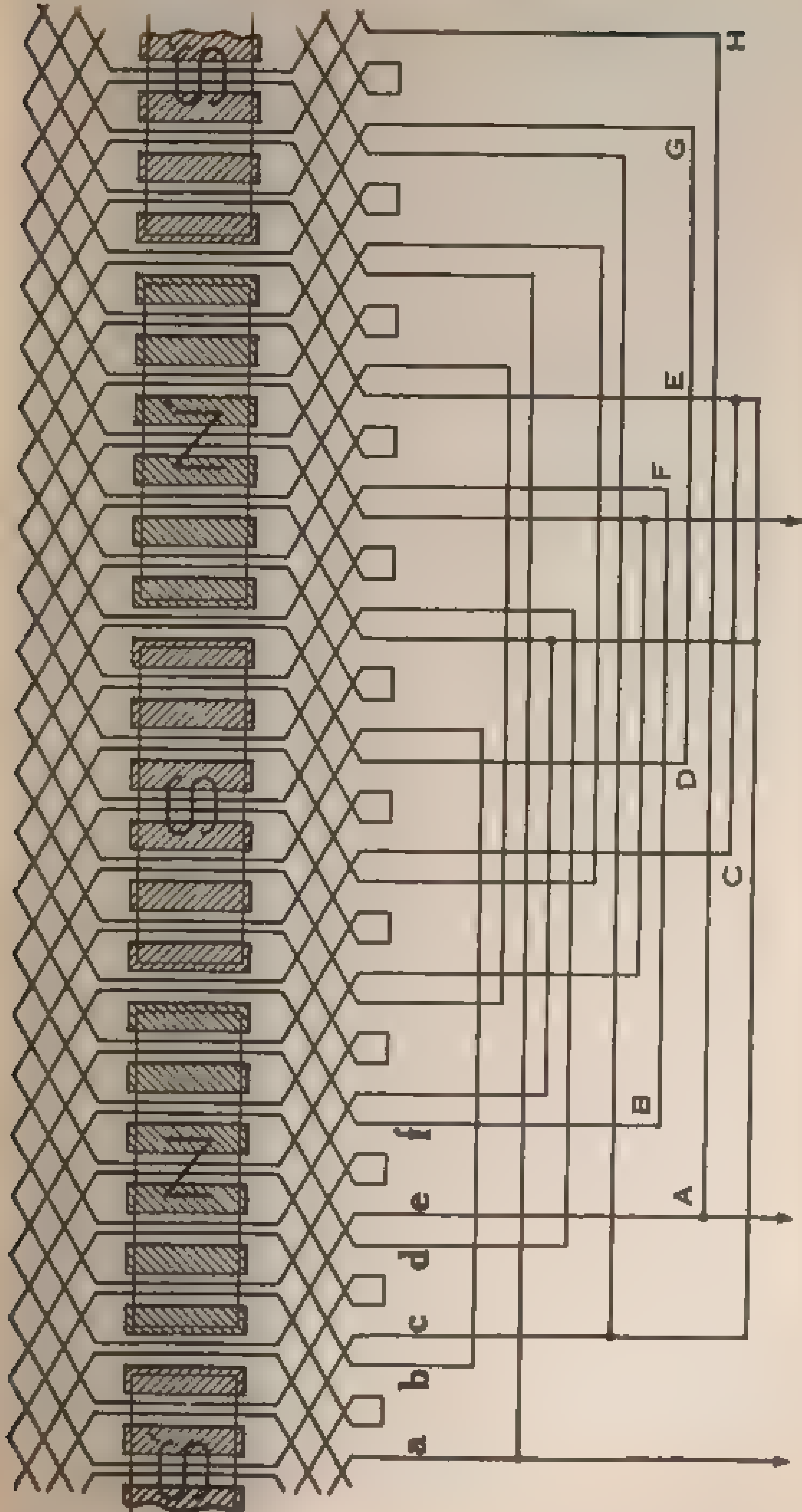


FIG. 871.—Stator winding for induction motor connected two-parallel-star for 220 volts.

together with *B* by the conductor *Y*. These points are 120° apart in electrical phase. Connections to the external circuit then lead from the three terminals 7, 8 and 9, which are likewise 120° apart in phase. The effect of this winding is as though four sections of one phase were placed in parallel as at *A*, Fig. 870. The four sections of the second phase are in parallel as at *B* and the four sections of the third phase are in parallel as at *C*, these sections being then placed in Y.

An alteration of the terminal connections which will not interfere with the spacing or connecting of the coils themselves is shown in Fig. 871. Here the terminals of the phase pole *e-f* leading to *A-B*, instead of being placed in parallel with the group under the other north pole at *F-E*, are placed in series therewith, the wire *E* leading to the middle point of the Y. Likewise the phase pole *c-d* is placed in series with the corresponding group under the other pole of like sign and the phase pole *a-b* likewise in series with its corresponding group. This altered arrangement of the polar group is shown in Fig. 872. Here two sets of coils belonging to each phase are connected in series and then placed in parallel with two other sets. This is done for all three phases. The three resulting groups are then placed in Y. The result will be to double the voltage to which the stator is adapted and halve the current for a given output. Such a connection will adapt the motor for 220 volts.

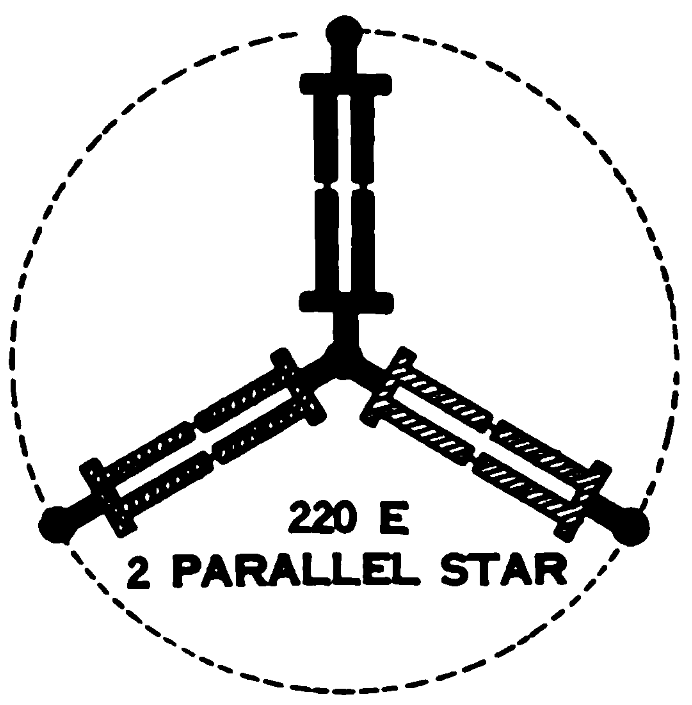


FIG. 872.—Relative position of parallel circuits.

Finally, instead of connecting the phase poles of each phase in parallel, they may be connected wholly in series. This is illustrated in Fig. 873. This will result in adapting the winding for 440 volts with but one-fourth of the current required in the first place. This is as though the entire groups belonging to one phase pole were connected in series with the similar groups under the other three poles as in Fig. 874.

Extra insulation should be placed between the various polar groups, in the stator winding, as the voltage between the various polar groups will be high with certain connections.

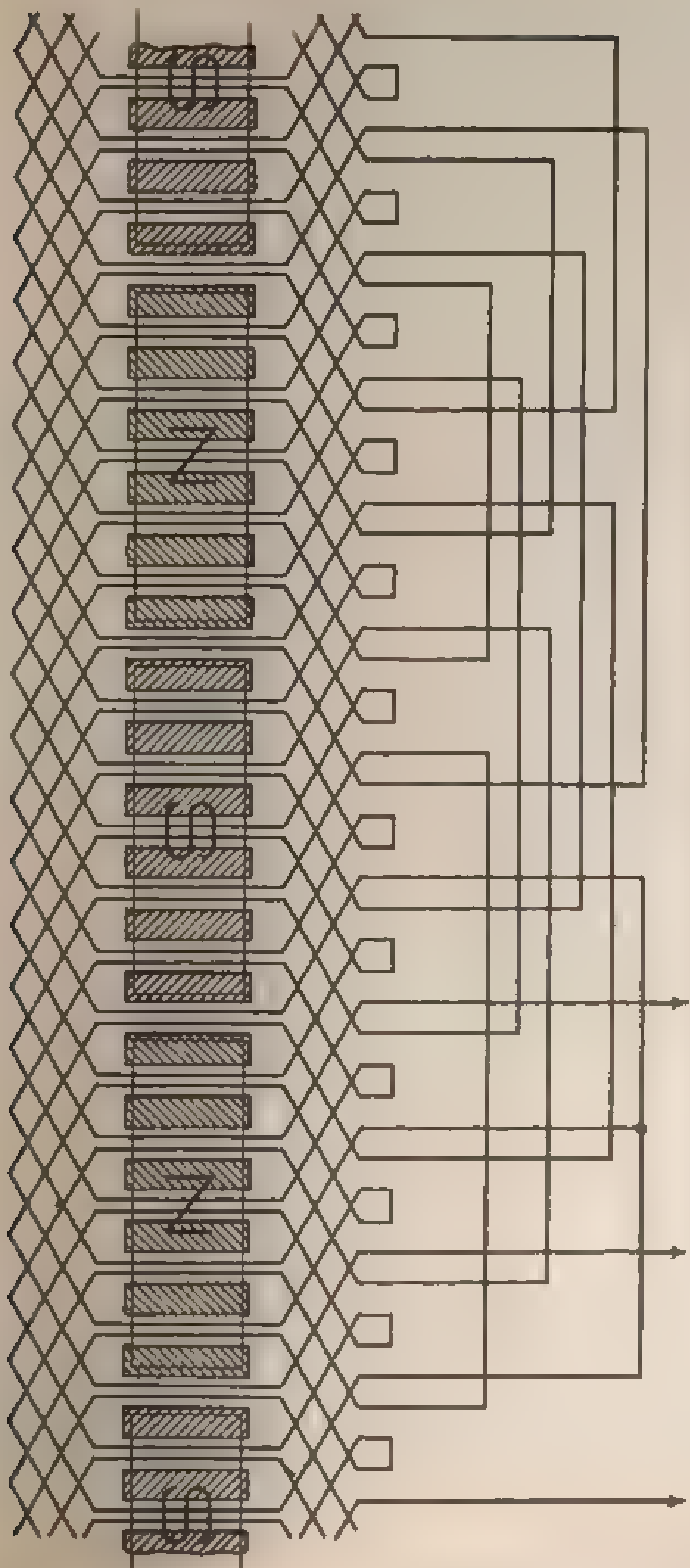


FIG. 873.—Stator winding for induction motor connected series-star for 440 volts.

Some idea of the flux distribution in such a stator will be obtained from Fig. 875, where the stator is shown divided into four equal parts as with a four-pole winding. The introduction of three phase currents into this distributed winding will give a maximum magnetic flux at the center of the pole with weaker poles of like sign immediately adjacent on either side, and will cause the points of maximum magnetic polarity to rotate.

If a motor is desired for a slower speed such as 1,200 r.p.m.

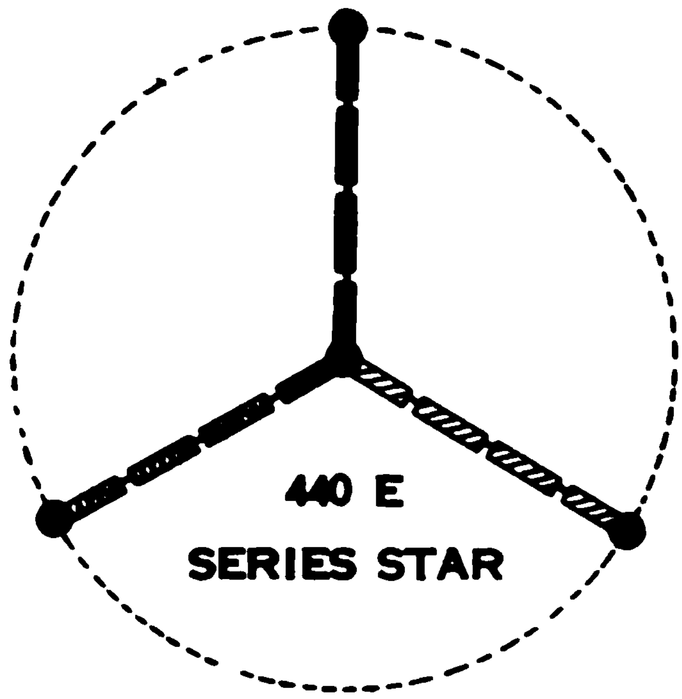


FIG. 874.—Relative position of series circuits.

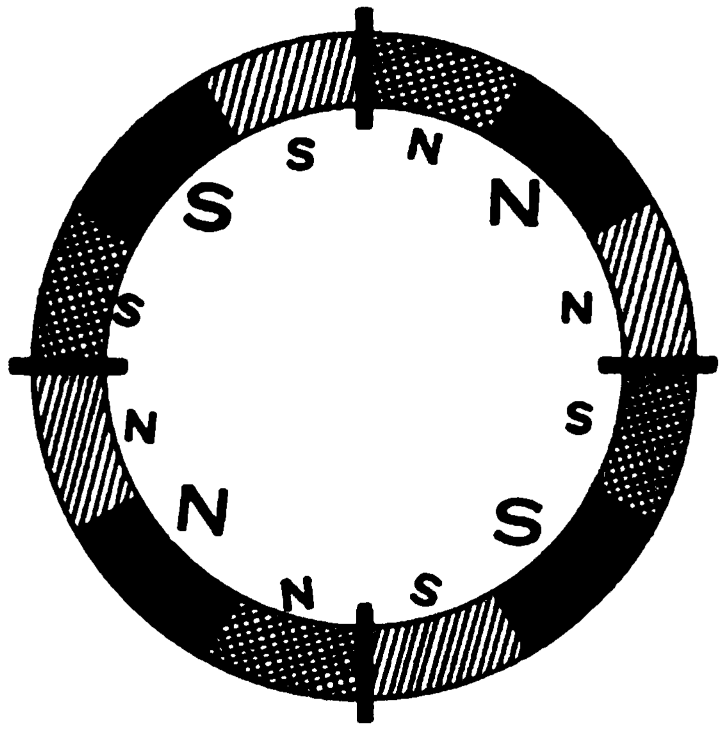


FIG. 875.—Relative polarities of interior of stator surface produced by currents in distributed windings.

six poles will be required in the stator. A commonly used arrangement employs 72 slots and coils.

$$\frac{72 \text{ coils}}{3 \text{ phases} \times 6 \text{ poles}} = 4 \text{ coils per phase per pole.}$$

Such a stator could also be wound with

$$\frac{72 \text{ coils}}{3 \text{ phases} \times 4 \text{ poles}} = 6 \text{ coils per phase per pole,}$$

and would then give 1,800 r.p.m.

To produce a symmetrical connection of coils the number of slots must be evenly divisible by the product of the number of poles and the number of phases, and therefore must be a whole number.

In some small motors the number of coils in the winding is not evenly divisible by the product of the number of poles and the

number of phases. Thus consider a machine with 24 coils wound for six poles and three phases. The number of coils per phase per pole would be:

$$\frac{24 \text{ coils}}{3 \text{ phases} \times 6 \text{ poles}} = 1\tfrac{1}{3}.$$

In order that there may be an equal number of coils per phase it is necessary to effect some combination in which the number of coils in the polar groups differ and yet which will give approximately equal impedances, resistances and reactances for each phase. Fig. 876 shows such a combination.

It will be noted that while the number of coils comprising a phase-pole group is not the same, the total number of coils per phase is the same and that the odd coils are placed symmetrically around the stator so as to balance the effect inductively and magnetically.

After connecting up a stator winding it should be tested to ascertain whether or not the connections are correct. If the winding is to be placed in Δ the three separate phases should be connected as in Fig. 877, the Δ opened and a testing battery introduced in series with a resistance box *R* to limit the current. If the windings are to be connected in Y, the testing circuit should be introduced at the middle point of the Y, and the three outside ends should

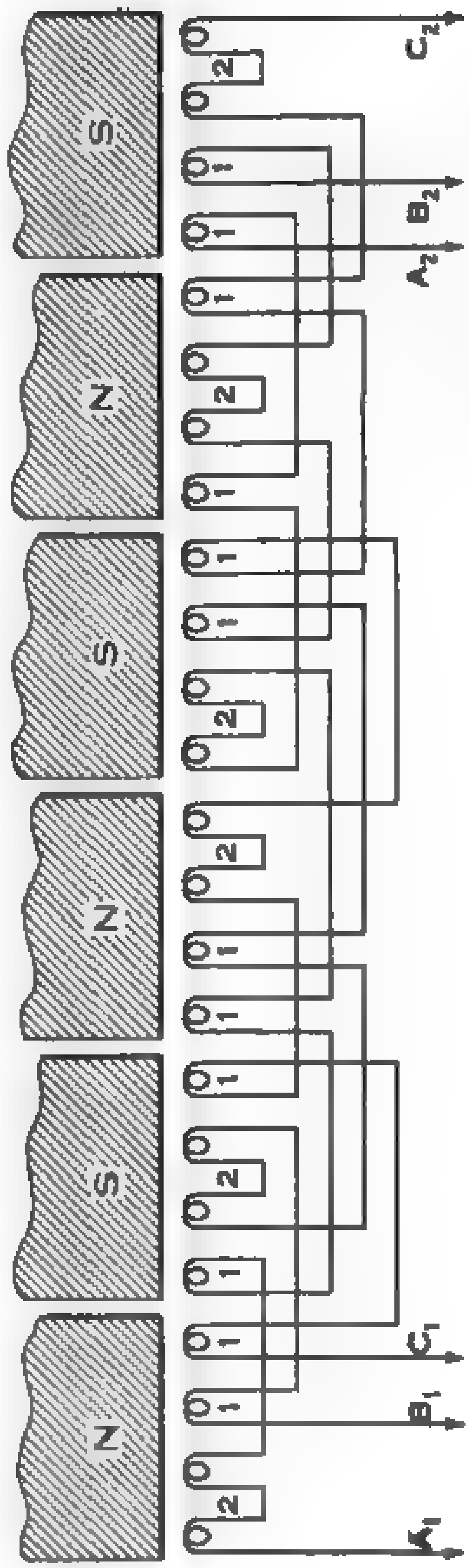


FIG. 876.—Illustrating connections necessary when the number of coils in the polar groups differ.

be connected in parallel as in Fig. 878. If the connections are correct, there will appear in the rotor space around the inside of the stator as many poles as the number of poles for which the rotor is wound, times the

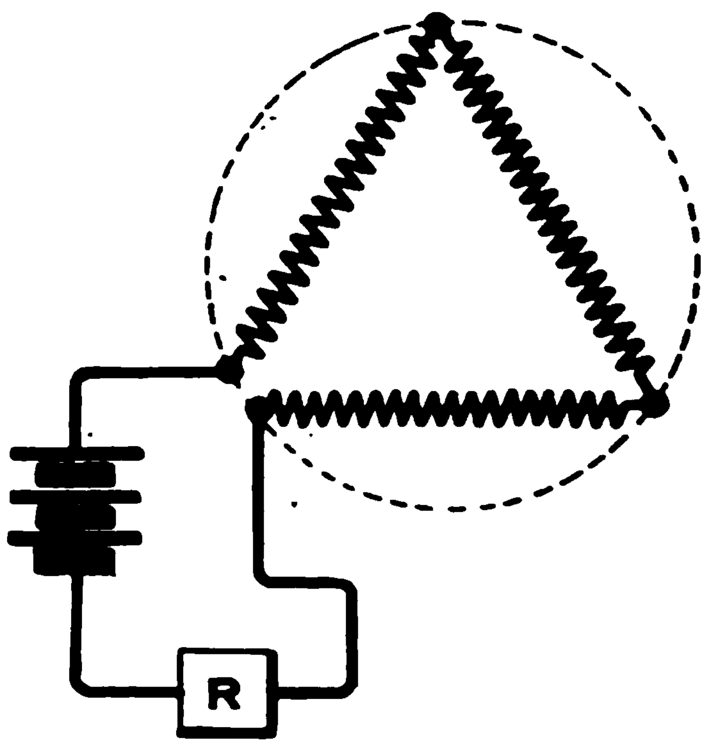


FIG. 877.—Method of testing Δ-connected stator to determine whether polarity of all coils in winding is correct.

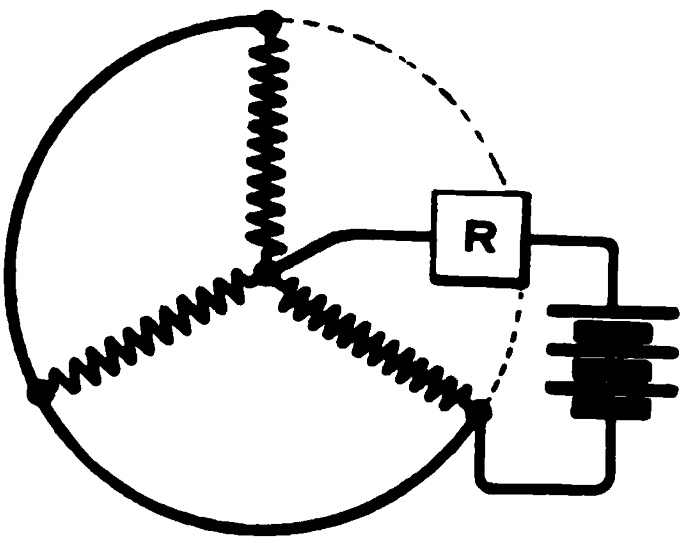


FIG. 878.—Method of testing Y-connected stator to determine whether polarity of all coils in winding is correct.

number of phases, alternating around the circumference. To explore the rotor a compass needle may be placed on a piece of iron as in Fig. 879, the projecting end being more readily approached to the stator iron and thus concentrating the flux generated beneath the needle. For a four-pole three-phase winding the needle would reverse its indications at regular intervals 4 times 3, or 12 times in one circumference of the stator. Any other result indicates a wrong connection. Dry cells, storage batteries or direct-current lighting circuits with a rheostat in series may be used for this test.

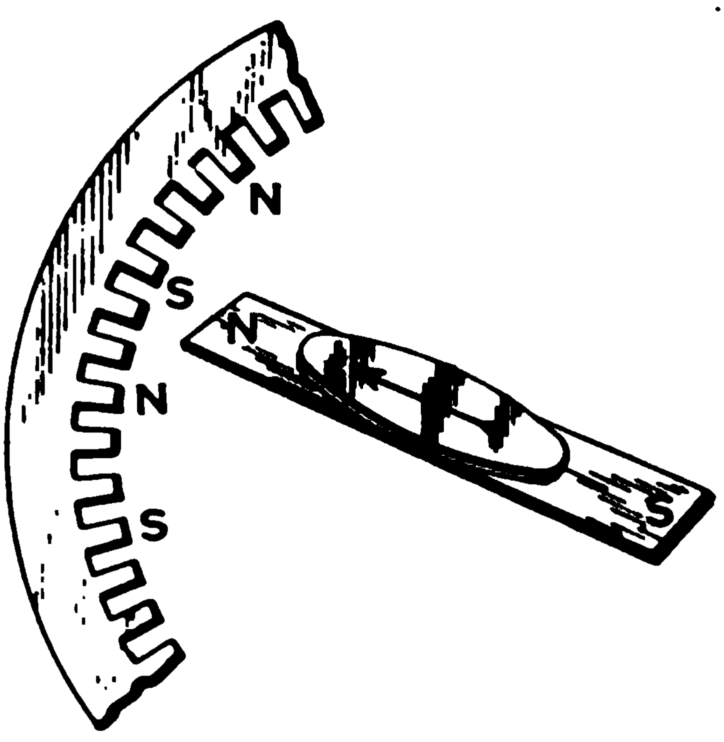


FIG. 879.—Arrangement of compass to detect polarity of stator sections.

In motors arranged for parallel connections of the polar groups, like poles may be connected together in series to allow for unbalancing of the magnetic circuit in case the bearings wear and the rotor settles, thus giving unequal air gaps. Small

motors are not usually so connected as all of the poles of each phase are in such cases connected in series.

Elementary Induction Motor Design

The weight of iron and copper required to build an induction motor of given output and given speed is fairly well established. As in direct-current machines, the capacity of such a motor depends on the area of active surface of the stator iron and the speed of the rotor. As the area of iron in the stator actually effective on the rotor is proportional to the square of the diameter of the bore and the length of the bore, an equation may be written expressing the relation of output to these quantities which is fairly accurate. The expression may be written as follows:

$$\text{H. P.} = D^2 \times L \times \text{r.p.m.} \times k.$$

Where D = diameter of the bore in inches.
L = length of the bore in inches.
k = "output coefficient."

The value of the output coefficient for various conditions may be found in tabular form in the Standard Handbook and other publications.

The permissible flux density at which the iron may be worked lies within fairly close limits. The density in the stator teeth ranges somewhere in the neighborhood of 110,000 lines per square inch, and the density in the yoke back of the teeth is usually between 80,000 and 100,000 lines.

The fundamental formula for the expression of the relation between flux, turns, voltage and frequency is similar to that for transformers, the only changes being those to take care of the distribution of the conductors through the iron and overlapping of the polar areas. The equation as applied to induction motors may be written as follows:

$$E = \frac{\Phi\ T\ n\ 4.44\ k\ k'}{10^8}.$$

Where E = applied voltage per phase of motor winding.
T = number of turns in series per phase.
n = frequency in cycles per second.
Φ = total flux per pole.
k = "distribution factor," 0.955 for three phase, 0.905 for two phase.
k' = chord factor.
C = number of conductors in series per phase.

The chord factor is numerically equal to the sine of one-half the electrical angle spanned by a single coil, a full-pitch winding being considered as spanning 180 electrical degrees, the sine of one-half of 180 degrees being unity.

Since the value 4.44 is true for all conditions and 10^8 is constant, the above equation may be written:

$$E = \frac{\Phi \; C \; n \; k \; k'}{45 \times 10^6}$$

The cross-sectional area of the conductors depends on the current and on the means for dissipating the heat in those con-

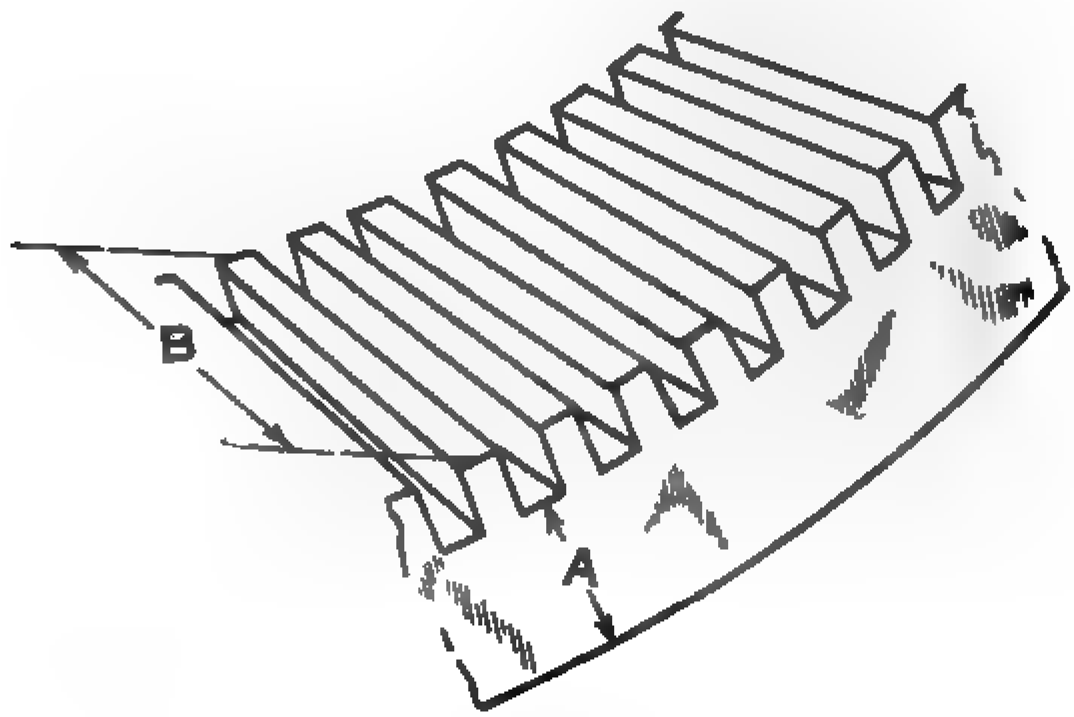


Fig. 880.

ductors and usually falls somewhere between 400 and 900 circular mills per ampere, the average being perhaps about 700 c.m.

An illustration of the use of these formulas may be given in connection with the design of a certain motor. This motor was designed as a one-half H. P., 200-volt, 60-cycle, three-phase machine.

The area of the iron back of the teeth as measured in Fig. 880 was 1⅞ inches wide, *B*, by 7/16 inch deep, *A*, giving a cross-section of 0.82 square inch. Since the flux from each pole divides in the yoke, the actual area available for each pole is 0.82 times 2 or 1.64 square inches.

Assuming a flux density of 80,000 lines per square inch, the total flux per pole would be 80,000 times 1.64 or 131,200 lines per pole.

As the stator has 24 slots, a throw of 1 to 7 would be full pitch for a single coil. For convenience in winding and to improve the performance, it is sometimes desirable to use a fractional pitch winding. In this case a throw of 1 to 6 was used. In a full-pitch winding for this motor, 6 slots would be passed over, and since in this design but 5 slots are passed over, each coil will span $\frac{5}{6}$ of 180 or 150 electrical degrees. The sine of one-half of 150 or 75 degrees is 0.9659, which is the chord factor used in the calculation as indicated.

The motor windings are to be connected in series-star, and the volts per phase will be:

$$\frac{200}{1.732} = 115.5 \text{ volts.}$$

All values have now been assumed with the exception of the number of turns per coil. Since there are to be one-half as many coils as slots, the number of conductors per slot will be the same as the number of turns per coil. Substituting the known values in the equation and transposing for the number of turns:

$$C = \frac{45 \times 10^6 \times E}{n \times \Phi \times k \times k'} = \frac{45 \times 10^6 \times 115.5}{60 \times 131{,}200 \times 0.955 \times 0.9659}.$$

$$C = 714 \text{ conductors per phase.}$$

Since there are 24 slots and 3 phases, there will be 24 divided by 3, or 8 slots per phase, and the number of conductors in each slot will be:

$$\frac{714}{8} = 89.$$

Thus there will be 89 turns per coil.

The current for a one-half H. P. 200-volt motor, designed for three-phase operation, will be obtained from the following formula:

$$I = \frac{\text{H.P.} \times 746}{1.732 \times E \cos \Phi \times \text{Eff.}}.$$

Where I = current in amperes per phase.
H. P. = horse power of motor.
E = terminal e.m.f.
Cos Φ = full load power factor of motor.
Eff. = full load commercial efficiency.

Assuming a power factor of 77% and an efficiency of 78%,

$$I = \frac{0.5 \times 746}{1.732 \times 200 \times 0.77 \times 0.78} = 1.8 \text{ amperes}$$

per terminal at full load. The ventilation provided in small motors is usually limited, radiation being relied upon to care for a considerable portion of the heat. For a safe temperature rise, 700 cm. per ampere would be a fair allowance. Then 700 times 1.8 would give 1,260 cm., which would be the required cross-sectional area of the conductors. This corresponds fairly closely to No. 19 wire. A check also shows that the slots are of ample dimensions to permit 89 turns of this size wire and the required slot insulation.

SECTION XVI CHAPTER V

ALTERNATING-CURRENT MOTORS

PRINCIPLES OF INDUCTION MOTORS

1. What is meant by "phase-pole" in a stator winding?
2. What is meant by "full-pitch" winding?
3. What is meant by "fractional-pitch" winding?
4. Explain the relation existing between the total number of coils, the number of phases, the number of poles and the number of phase-poles in an induction motor winding. What variations are possible and what are the limitations?
5. Explain what is meant by the following kinds of windings, and the voltages for which they are adapted:

   4-parallel-star, 2-parallel-star, Series-star.
6. What is the relation existing between the number of poles, the frequency of supply and the r.m.p. in an induction motor?
7. Explain the method of testing a stator winding connected in either Y or Δ to ascertain whether the connections between the various phase-poles have been correctly arranged.

A. C. MOTORS

CONTROL OF VARIABLE SPEED INDUCTION MOTORS

Induction motors without load will run at practically synchronous speed, this speed being determined solely by the frequency of supply. At full load the speed drops 2% or 3%, which is much less than that encountered in direct-current shunt motors.

Control by Resistance in Secondary.—The commonest and most flexible method of varying the speed of a polyphase induction motor is by inserting resistance in the secondary circuit. This involves a polar wound, formed coil rotor with three slip rings as shown in Fig. 881. Brushes *B-B-B* on these rings lead to an externally located speed regulating rheostat or con-

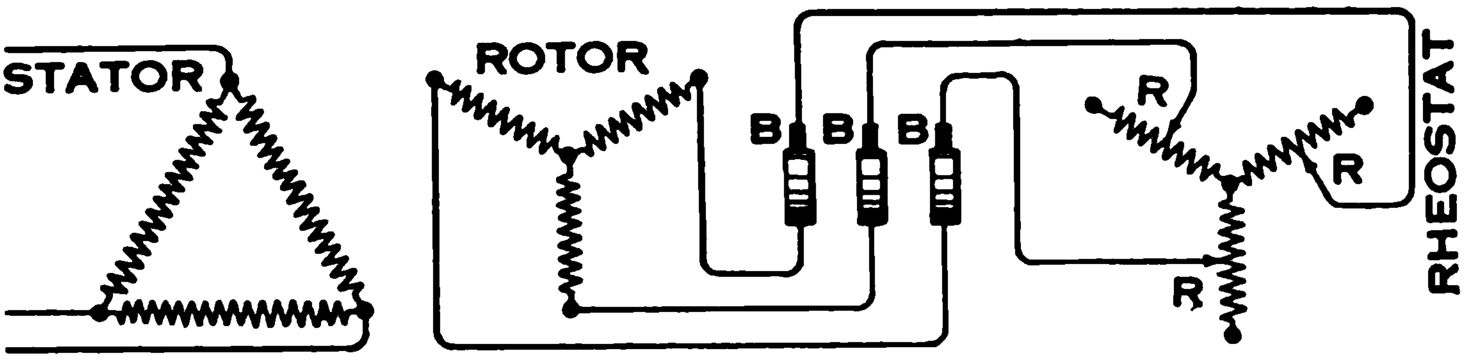


FIG. 881.—Wiring connections for speed control of induction motor by rheostat in secondary circuit.

troller, usually Y connected. The stator is supplied with line voltage and, like the primary of any transformer, absorbs current in proportion to the demands on the secondary. By varying the position of the three rheostat arms *R-R-R*, the current in the rotor may be adjusted to any desired value. With the secondary circuit open and no current in the rotor the stator will absorb only the exciting current plus that necessary to supply the mechanical losses.* As an increasing current is allowed to flow in the rotor by moving the points *R-R-R* toward the center of the Y with increase in load, the reaction on the stator lowers its opposition to the line voltage and the stator absorbs current in proportion to that in the rotor. This is in effect the equivalent to the control of speed of a shunt-wound direct-current motor by inserting a rheostat in the armature circuit.

It has the same flexibility, and both torque and speed can be varied over the widest range. It has the same low efficiency. Thus if a motor developed 90% efficiency at full speed, it would develop approximately only 45% efficiency at half speed. It has the disadvantage of very low efficiency for large torque at low speed and, for a fixed setting of the rheostat, is subject to wide variations in speed under changes in load at low speed. It is quite commonly used for mine hoists, steel mills and elevators. The load may be rapidly accelerated with a small current in the stator. This method, however, deprives the motor of its great advantage, namely, the simple construction embodied in a cage-wound rotor.

There is no method of speed control for an induction motor corresponding to a rheostat in the field circuit of a shunt-wound

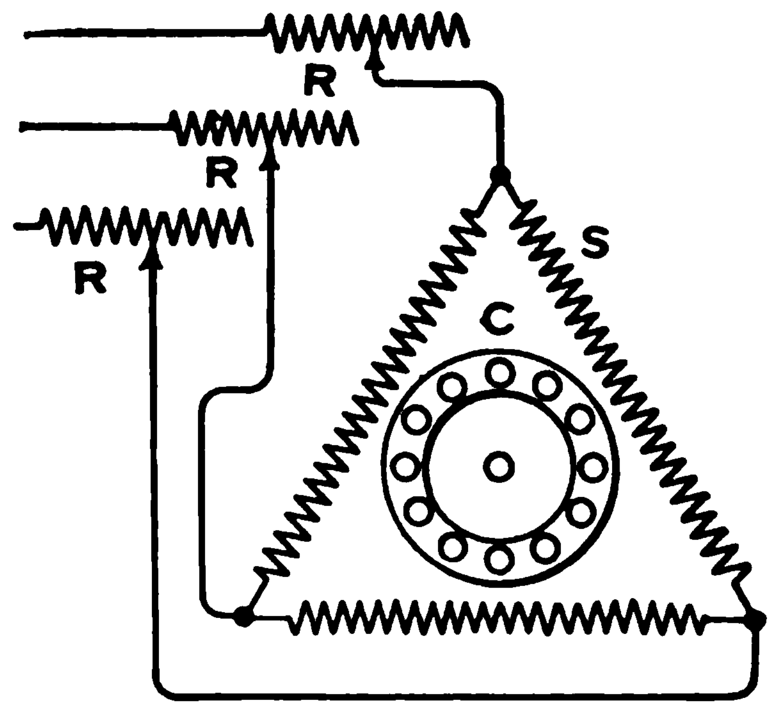


FIG. 882.—Wiring connections for speed control of induction motor by rheostat in primary circuit.

direct-current motor as it is impossible to separate in the stator winding, the magnetizing current which produces the field flux, from the rotor current which flows in the same winding and is inductively transformed to the rotor circuit.

Control by Rheostat or Compensator in Primary.—Another method of varying the speed of an induction motor is to vary the e.m.f. on the primary. This is accomplished by inserting a reactive compensator or rheostat *R-R-R* in the line between the source of supply and the stator winding *S* as in Fig. 882. This method of control admits of the use of a cage-wound rotor *C*, which is simple and reliable. In order to obtain a large starting

torque with this method of control, the rotor conductors and short-circuiting end rings are usually made of high resistance material. This will of course give a considerable percentage of slip at full load and maximum voltage. If a rheostat is employed to reduce the line voltage, the motor will require approximately two to four times full-load current in order to produce full-load torque at start. If a compensator is employed, the same full-load torque will be obtained at start with 1.4 times full-load current. If the preceding method of control employing a rheostat in the rotor circuit is used, full-load torque at start may be obtained with exactly full-load current The employment of a rheostat in the rotor circuit has a much better inherent regulation over the latter method of control as when the load is changed from full load to 50% overload, the speed variation of the slip-ring type of rotor is approximately but 2½%, while in the second method of control with a high resistance rotor, the same change in load would cause a 10% change in speed.

As to the relative advantages of the resistance type of controller and the autotransformer or compensator type for starting and speed control, the following points should be considered. With the resistance type the voltage is brought gradually up to the value required to start the motor and then continually increased as the motor speeds up until full potential is reached at full speed. This is because the drop in the starting resistance depends upon the current therein, and with a large current the drop is large and the difference between this drop and the line e.m.f., which reaches the motor is small. As the motor rises in speed the counter e.m f. rises and reduces the intake. The current through the starting resistance thus falls and the drop across it falls. Therefore the voltage at the motor rises. Now the torque of a motor is proportional to the square of the applied e.m.f. Therefore, as the motor accelerates, there is automatically applied a rising e.m f. which assures a very rapid acceleration. With the compensator type a certain reduced voltage is applied to the motor terminals by means of an autotransformer. This voltage depends upon the tap of the transformer utilized and is independent of the current which the motor demands. This voltage remains constant until the motor has reached its full speed or until it is switched to a higher potential tap in the controller.

From the standpoint of operating cost the cage-wound rotor and compensator control is the more expensive and the form-wound rotor with externally placed rheostat is the cheapest. This is because the losses encountered with the cage-wound high-resistance rotor are greater and a larger motor is therefore necessary to obtain the reduction in speed required, while with the form-wound rotor and externally placed rheostat, the losses are external to the machine. Furthermore, the compensator method of control is complicated, due to the fact that the compensator coils must be cut out one after another and cannot be short-circuited as may be the separate coils of a rheostat.

With resistance in the primary circuit there is nothing in the motor to get out of order. It may be therefore located in an inaccessible place. This plan of control is especially useful in powder mills and oil refineries where arcing must be made impossible. There is nothing in the motor to spark, and the control contacts can be operated under oil if required. The speed is liable to change widely under changes in load, especially if the speed for which the rheostat is set is low. The efficiency and power factors are both slightly lower than in the preceding method.

Standard induction motors must be operated at approximately the frequency for which they are designed. A variation of 10% is usually the maximum permissible. A 60-cycle motor on a 25-cycle circuit would have its magnetizing current increased to such an extent as to make operation impossible and the output would be reduced in proportion to the frequency. On the other hand a 25-cycle motor on a 60-cycle circuit would not be mechanically strong enough to withstand the increase in speed, which would be 240% of normal.

Control by Changing Frequency.—Motors may be liberally designed so as to permit of a limited number of speeds by changing the frequency of supply. The various frequencies are obtained from several alternators, and a cable connects the motor with the source. The plan is similar to the Crocker-Wheeler multi-voltage direct-current system. Two wires are generally used for each frequency and one common return for all frequencies. It has been used occasionally in machine shops with fair results. The speed varies directly with the frequency of supply.

Contro by Different Polar Combinations.—Motors may have their windings reconnected for different numbers of poles, but they will not operate satisfactorily unless the pitch of the coils is changed. Leaving the coils as originally placed will work the iron to a very high density in portions of certain magnetic circuits. This will result in an increased exciting current, a reduction in power factor and efficiency, and noisy operation.

Additional insulation must be placed between adjacent coils, where altered connections bring about increased potentials.

Motors may be designed for operation with different numbers of poles, by supplying the stator with two separate windings, each connected for a different number of poles and having separate terminals. This arrangement would of course increase the

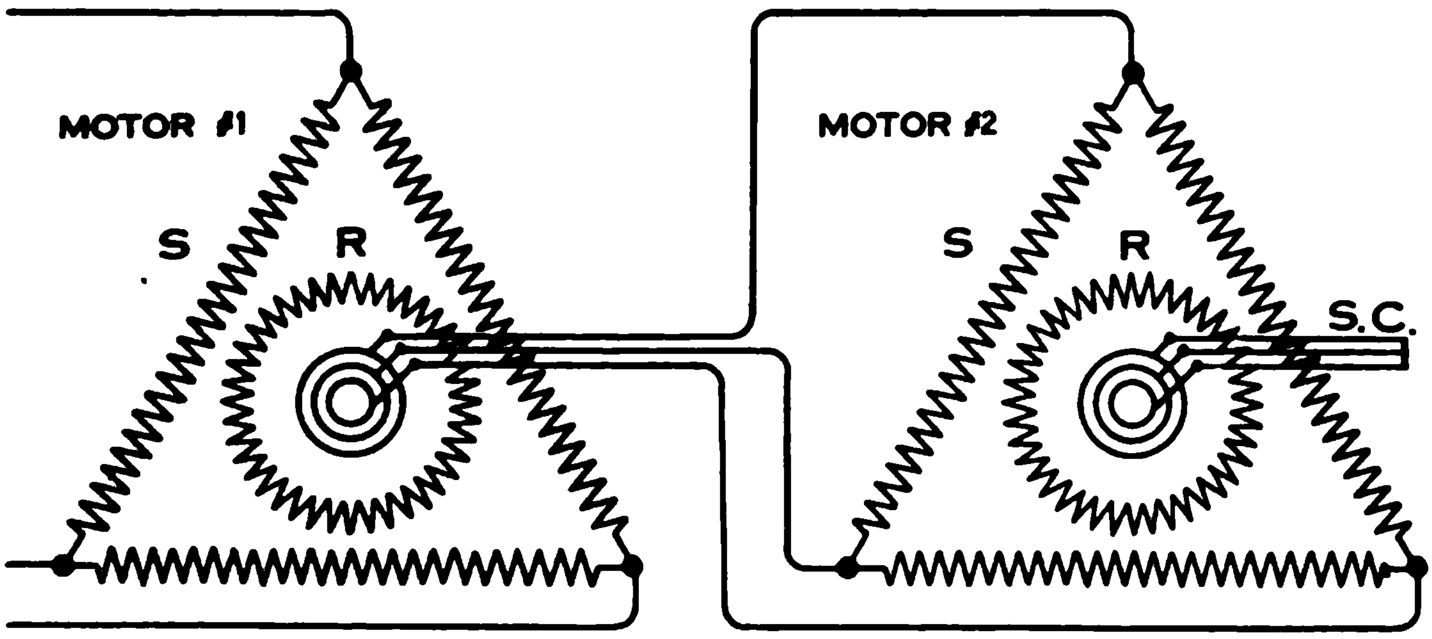


FIG. 883.—Cascade connection of induction motors.

size, weight, and cost and decrease the efficiency and power factor of the machine.

A single winding may be arranged to be reconnected for two or three different numbers of poles. Under these circumstances cage-wound rotors only can be employed, as a polar winding could not be readily readapted for different numbers of poles. Where battleships are electrically propelled, a few fundamental speeds have been obtained by connecting the stators of the propelling induction motors for various numbers of poles and thus avoiding rheostatic losses in the circuit.

Control by Cascade Connections.—Where high operating efficiency and constancy of speed under load changes are desired, the **cascade connection** of motors may sometimes be employed to advantage. The scheme is illustrated in Fig. 883. Here the

stator winding of motor No. 1 is connected to the source of supply. This motor must be furnished with a wound rotor having slip rings. The current from these slip rings is led to the stator of motor No. 2, which is also supplied with a polar wound rotor. The slip rings of this rotor are short-circuited or the rotor cage-wound. The two motors are wound for different numbers of poles and their shafts are rigidly connected. With two such machines, four fundamental speeds can be obtained. If motor No. 2 has four poles and is designed for 25 cycles, its speed when running alone will be

$$\frac{\text{Alternations per minute}}{\text{Number of poles}} = \text{r.p.m.} = \frac{3000}{4} = 750.$$

If the motors are connected as shown in the figure and the direction of phase rotation is the same, they will tend to revolve in the same direction and are then said to be connected in **direct concatenation.** If any two of the wires between the two motors are cross connected, the direction of phase rotation will be reversed and one motor will tend to run in an opposite direction to the other. They are then said to be connected in **differential concatenation.** Assuming these two motors to be thus differentially connected, the speed will be equal to the alterations per minute divided by the difference in the number of poles. Thus:

$$\frac{\text{Alternations per minute}}{P_1 - P_2} = \frac{3000}{12 - 4} = 375 \text{ r.p.m.}$$

Motor No. 1 running single would revolve

$$\frac{3000}{12} = 250 \text{ r.p.m.}$$

If the motors were connected in direct concatenation, the speed would be:

$$\frac{\text{Alternations per minute}}{P_1 + P_2} = \frac{3000}{12 + 4} = 187.5 \text{ r.p.m.}$$

If motor No. 1, having the greater number of poles, is connected to the line, then motor No. 2 produces a rotating field in the secondary of motor No. 1, opposite to that of its primary. If motor No. 2 is connected directly to the line, the effect is to boost the frequency in the circuit connecting the two motors. This makes it possible to obtain a speed which is higher than the speed of motor No. 1 running as a single motor.

The torque developed by each motor of a cascade connection is proportional approximately to the ratio of its number of poles to the total number of poles in the set, multiplied by the total torque. Thus with two motors connected up in direct concatenation, one having twelve poles and the other four, the torque developed by the first motor will be $^{12}/_{16}$ of the total torque of the set, while that of the second motor will be $^{4}/_{16}$. With differential concatenation the torque of each motor will be the same, but as they act in opposition the total resultant torque will be proportional to the ratio of the difference of the number of the poles. Thus, with the motors considered above, the total torque with differential concatenation would be $\frac{12 - 4}{16} = \frac{1}{2}$ of the torque developed by the motors when connected in direct concatenation. The differential concatenation gives, in general, the lowest starting torque and, if the motor having the greatest number of poles is connected to the line, the set will not come up to synchronism by itself. It will rise to the synchronous speed of the single motor, which is connected to the line, but will not exceed this speed. Therefore it is necessary to connect the motor having the smaller number of poles to the line, and when the set has nearly reached full speed for differential concatenation, to switch over to normal connection—that is, having the motor with the greater number of poles connected to the line.

Slip Regulator.—When discussing the reversing mill motor it was explained that some method of regulating the input into the induction motor which operated the fly wheel and generator was necessary in order to prevent great fluctuations in load. The way in which this is accomplished is illustrated in Fig. 884. The current from the main motor operating the fly wheel and generator is taken through series transformers *T-T-T*. The secondaries of these transformers are connected in Y and supply a small three-phase induction motor *A* with current. This latter is called a torque motor, for it does not revolve but simply exerts a torque in a definite direction. Rigidly attached in a locked position to its shaft is a lever on one end of which are supported three electrodes arranged to move in a vertical plane in three liquid rheostats *B-B-B*. The remaining three electrodes of these rheostats connect to the slip rings *R-R-R* of the main motor's rotor. At normal load the torque of the locked motor,

aided by the counter weight W, sustains the movable electrodes at a definite level. When a heavy load comes on the generator it reacts on the fly wheel and main motor M to slow them down. The increase in current now taken by the main motor supplies the torque motor with an increasing current also. This motor rotates its rotor in a direction to raise the electrodes in the liquid rheostats, thereby inserting additional resistance in the rotor circuit of the main motor and checking the increase of current therein. This check is inductively handed back to the stator, and the main motor is thus prevented from taking in

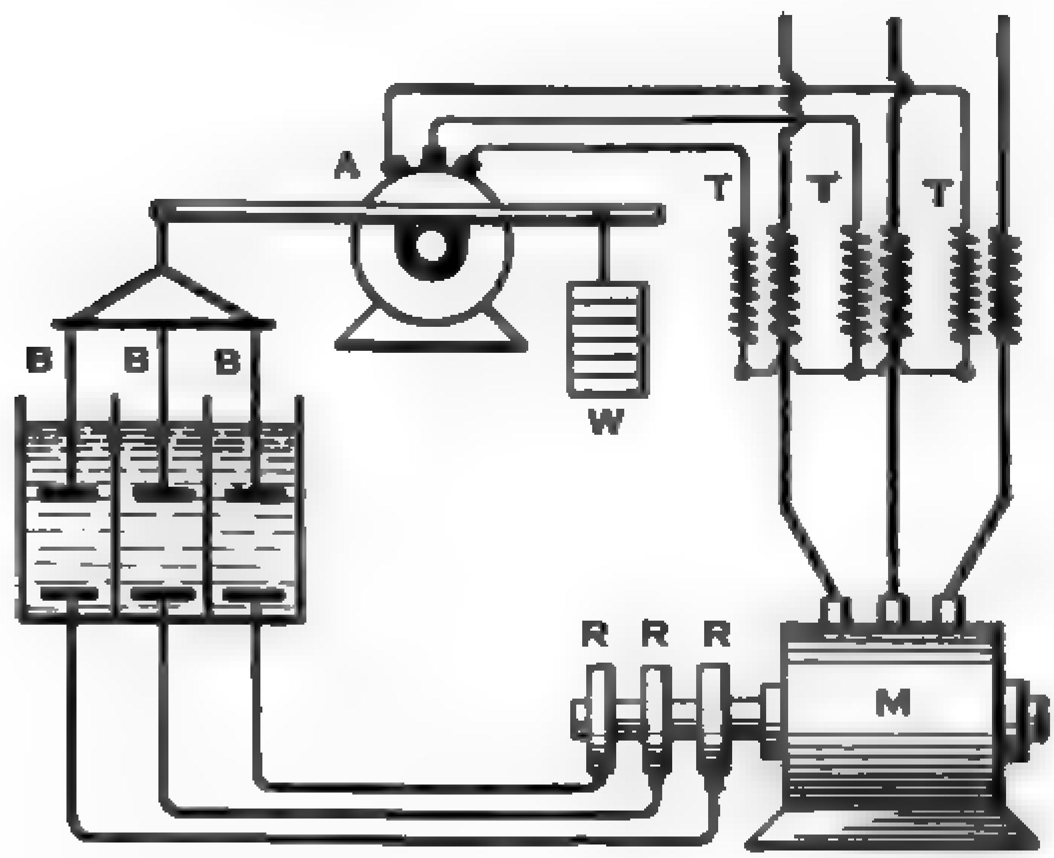


FIG. 884. "Torque motor" for automatically varying resistance of liquid rheostat in secondary circuit to vary speed of main induction motor.

the large increase of current which the load demands. When the main motor is thus prevented from developing additional power, the fly wheel delivers to the load a part of the energy stored therein.

As an illustration of the practical benefit derived from such a device, the fluctuations in load upon a certain main motor varied from 800 and 1,200 kilowatts when no regulator was in circuit. When the regulator was introduced the peaks were reduced to a maximum of 800 kilowatts with an average of about 500 kilowatts. The average was thus reduced from 1,000 to 500 kilowatts and the maximum load from 1,200 to 800 kilowatts.

SECTION XVI CHAPTER VI

ALTERNATING-CURRENT MOTORS

CONTROL OF VARIABLE SPEED INDUCTION MOTORS

1. What determines the speed of an induction motor without load? What determines its speed when loaded?
2. Explain the method of varying the speed of an induction motor by inserting resistance in the secondary circuit. What type of rotor is required?
3. Explain the method of varying the speed of an induction motor by varying the e.m.f. of the primary circuit. What type of rotor may be employed? Sketch.
4. Explain the method of varying the speed of an induction motor by varying the frequency of supply.
5. What will be the effect upon the speed of an induction motor if the number of poles in the primary winding are altered. How may this be done?
6. Explain the method of varying the speed of an induction motor set by "cascade" connection. What kind of rotors are required?
7. What is meant by "direct concatenation"? What is meant by "differential concatenation"? What are the relative effects upon the speed of a motor?
8. Explain the principle of the "slip regulator" for limiting the power input to an induction motor. Sketch.

A. C. MOTORS

THE CIRCLE DIAGRAM FOR THREE-PHASE INDUCTION MOTORS

The circle diagram is a method for graphically indicating the performance of induction motors. This diagram is constructed in various ways, among which are forms devised by Heyland, McAllister and Specht. The following explanation is based on the McAllister method as applied to three-phase motors.

The circle diagram is one in which there is but a single line or vector to represent the current in the machine at any given load. Inasmuch as there are three separate line currents in a three-phase motor, it is necessary to combine these currents into a single resultant value, which will represent, at the stated line voltage, the same power and losses as in a three-phase machine. This value is called the "equivalent single-phase current."

To represent the same total losses in a three-phase motor based upon this equivalent single-phase current, the motor must be assumed to have an "equivalent single-phase resistance."

In the following equations,

I = current in any line conductor.
i = current in each phase.
R = resistance measured between two terminals.
r = resistance per phase.
$I\sqrt{3}$ = "equivalent single-phase current."
$\frac{R}{2}$ = "equivalent single-phase resistance."

Equivalent Single-Phase Current

In any three-phase circuit, the current in any line conductor times the square root of three is called the **equivalent single-phase current** or **total current.**

Since $I \times \sqrt{3} \times E = P$ for any balanced load, at 100% power factor, if the voltage remains constant, the first member of the equation may be combined into two factors, as:

$$(I\sqrt{3}) \times E = P \tag{1}$$

$I\sqrt{3}$ being the "equivalent single-phase amperes."

Equivalent Single-Phase Resistance

In any three-phase receiver, the resistance between any two terminals divided by two is the **equivalent single-phase resistance.**

For any symmetrical Y connection, the copper loss per phase is $i^2 \times r$; and the total loss for the three phases is $3(i^2r)$.

$$I = i \text{ and } R = 2r, \text{ therefore } r = \frac{R}{2} \qquad (2)$$

By substitution, the total copper loss is:

$$3\left(I^2 \times \frac{R}{2}\right) \text{ or } (I\sqrt{3})^2 \times \frac{R}{2} \qquad (3)$$

For any symmetrical Δ connection, the total copper loss as for Y is $3(i^2r)$.

$$I = i\sqrt{3}, \text{ and, by transposition, } i = \frac{I}{\sqrt{3}} \qquad (4)$$

In accordance with the laws of parallel circuits, the resistance between terminals is:

$$R = \frac{2r \times r}{2r + r} = \frac{2r^2}{3r} = \frac{2}{3}r \text{ and } r = \frac{3R}{2} \qquad (5)$$

By substitution, the total copper loss is:

$$3\left(\left[\frac{I}{3}\right]^2 \times \frac{3R}{2}\right) = 3\left(\frac{I^2}{3} \times \frac{3R}{2}\right) = 3\left(I^2 \times \frac{R}{2}\right) \text{ or } (I\sqrt{3})^2 \times \frac{R}{2} \qquad (6)$$

as in Y connection.

To illustrate the application of these formulas, assume a three-phase Y-connected winding having a resistance of 2 ohms per phase and carrying a current of 10 amperes in each line wire. The total losses will be $3(i^2r)$, therefore $3(10^2 \times 2)$ equals 600 watts total copper loss. As the resistance of one phase is 2 ohms, the measured resistance between any two terminals is $2r$ or 4 ohms.

Substituting in formula (1):

$$2 = \frac{4}{2},$$

and in formula (2):

$$3\left(10^2 \times \frac{4}{2}\right) \text{ or } (10\sqrt{3})^2 \times \frac{4}{2} = 600 \text{ watts.}$$

Assuming the same machine to be Δ-connected, the terminal resistance, as in formula (5), would be

$$\frac{2}{3} \times 2 = 1\tfrac{1}{3} \text{ ohms},$$

and the phase resistance would be

$$2 = \frac{3 \times \frac{4}{3}}{2}.$$

The line current, as in formula (4), would be

$$10\sqrt{3} \text{ or } 17.32 \text{ amperes.}$$

Substituting in formula (6),

$$3\left(\left[\frac{17.32}{3}\right]^2 \times \frac{3 \times \frac{4}{3}}{2}\right) = 3\left(\frac{17.32^2}{3} \times \frac{3 \times \frac{4}{3}}{2}\right) =$$

$$3\left(17.32^2 \times \frac{\frac{4}{3}}{2}\right) \text{ or } (17.32 \times 1.732)^2 \times \frac{\frac{4}{3}}{2} = 600 \text{ watts.}$$

Using the "equivalent single-phase current" and "equivalent single-phase resistance," the circuit may now be calculated as a single-phase circuit, the line voltage being used in all cases.

Rotor Current

The current in the rotor of an induction motor may be accurately represented under all load conditions by a straight line such as O-I, Fig. 885, drawn within a circle, one end being constantly at a given point in the circumference as O, and the other end in the circle at a point as I, the location of which depends on the characteristics and load of the motor.

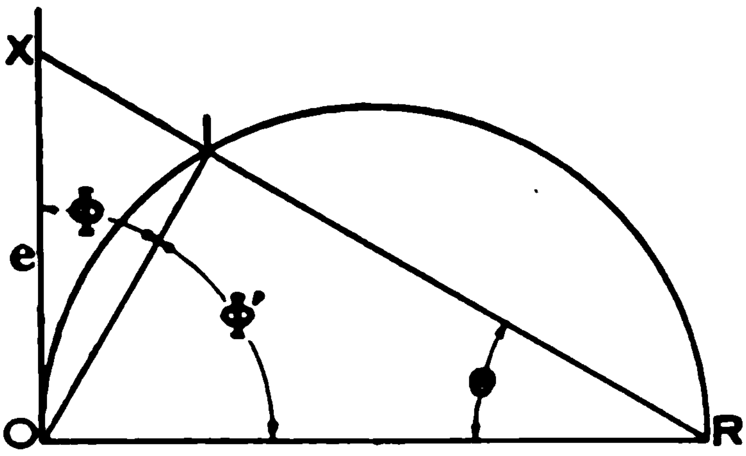


Fig. 885.

As the currents under various conditions may be represented by vectors starting at the point O, and terminating at various points along the circumference of the circle OIR, it is generally stated that the terminals of these current vectors, commonly called the "current locus," always lie in a circle.

It is a well-known theorem in geometry that any triangle inscribed within a semicircle, the diameter of which is the hypothenuse, will be a right triangle.

Since OIR is always a right angle and OR is constant, the point I must trace the outline of a semicircle for any value of OI. This proves that the current locus lies in a circle.

Since, for a given voltage, the flux of an induction motor is practically fixed, the rotor may be considered as an A. C. generator having a variable speed (slip) and a constant field strength, the inductance and resistance also being constant.

In Fig. 885, let OX equal the rotor reactance in ohms at some given slip, and OR at right angles thereto, equal the rotor resistance. Lay off the rotor induced voltage, e, along OX. Since e varies directly with the slip and also OX varies directly with the slip (for $X = 6.28\ nL$) then OX varies directly with e.

$e = k\ (OX)$, where k is some constant, and since:

$$I = \frac{e}{\sqrt{OX^2 + OR^2}} \tag{7}$$

then

$$I = \frac{k\ (OX)}{\sqrt{OX^2 + OR^2}}. \tag{8}$$

Since the line XR, Fig. 885, represents the impedance of the rotor, $XR = \sqrt{OX^2 + OR^2}$ and I varies directly with

$$\frac{OX}{\sqrt{OX^2 + OR^2}}; \tag{9}$$

then I varies directly with $\dfrac{OX}{XR}$ and θ.

Therefore the rotor current varies directly with sin θ. Drawing OI perpendicular to XR and constructing a semicircle OIR upon the diameter OR, we have two similar triangles OIX and OXR, in which the angle, $\Phi = $ angle θ.

This may be proven as follows:

Since the sum of the angles of OIX and OIR is 180°,

$$\Phi + \Phi' = 90° \quad \text{and} \quad \theta + \Phi' = 90°.$$

Therefore

$$\Phi + \Phi' = \theta + \Phi' \quad \text{and} \quad \Phi = \theta. \tag{10}$$

This may be proven for any value of OX in a similar manner.

Sin $\theta = \frac{OI}{OR}$ and OR, representing the rotor resistance, is constant, therefore I varies directly with OI since I varies with sin θ, and by selecting a suitable scale the line OI may accurately represent the rotor current.

$\frac{OR}{XR} = \cos\theta = \cos\Phi$ (see formula 10) = cos angle of lag, and if e be drawn to represent volts along OX, the angle Φ represents the phase angle between the rotor current and rotor voltage for any slip and consequently any load.

The fact that the slip equals $\frac{\text{Sec. losses}}{\text{Sec. input}}$, may be shown in the following manner:

Is = secondary amperes.
Es = secondary volts at 100% slip.
X = secondary reactance at 100% slip.
Wo = secondary watts output.
S = % slip.
Rs = secondary resistance.
Ws = secondary watts input.
θ = secondary angle of lag.

It is evident that

$$Is = \frac{S \times Es}{\text{Rotor impedance}}.$$

Since the rotor impedance equals Rs times $\frac{1}{\cos\theta}$,

$$Is = \frac{S \times Es}{Rs \times \frac{1}{\cos\theta}}.$$

Transposing for the value of S:

$$S = \frac{Is \times Rs}{Es \times \cos\theta}.$$

Multiplying the numerator and denominator by Is,

$$S = \frac{Is^2 \times Rs}{Is \times Es \times \cos\theta}.$$

Since $Is \times Es \times \cos\theta = Ws$, and $Ws = Wo + Is^2Rs$:

$$S = \frac{Is^2Rs}{Wo + Is^2Rs} = \frac{\text{Secondary copper loss}}{\text{Secondary watts input}}.$$

Obtaining Data for Circle Diagram

To secure the data for constructing the circle diagram run the motor without load at normal volts and read the total watts intake, volts across terminals and amperes per terminal. A series of these readings beginning with about 120% normal

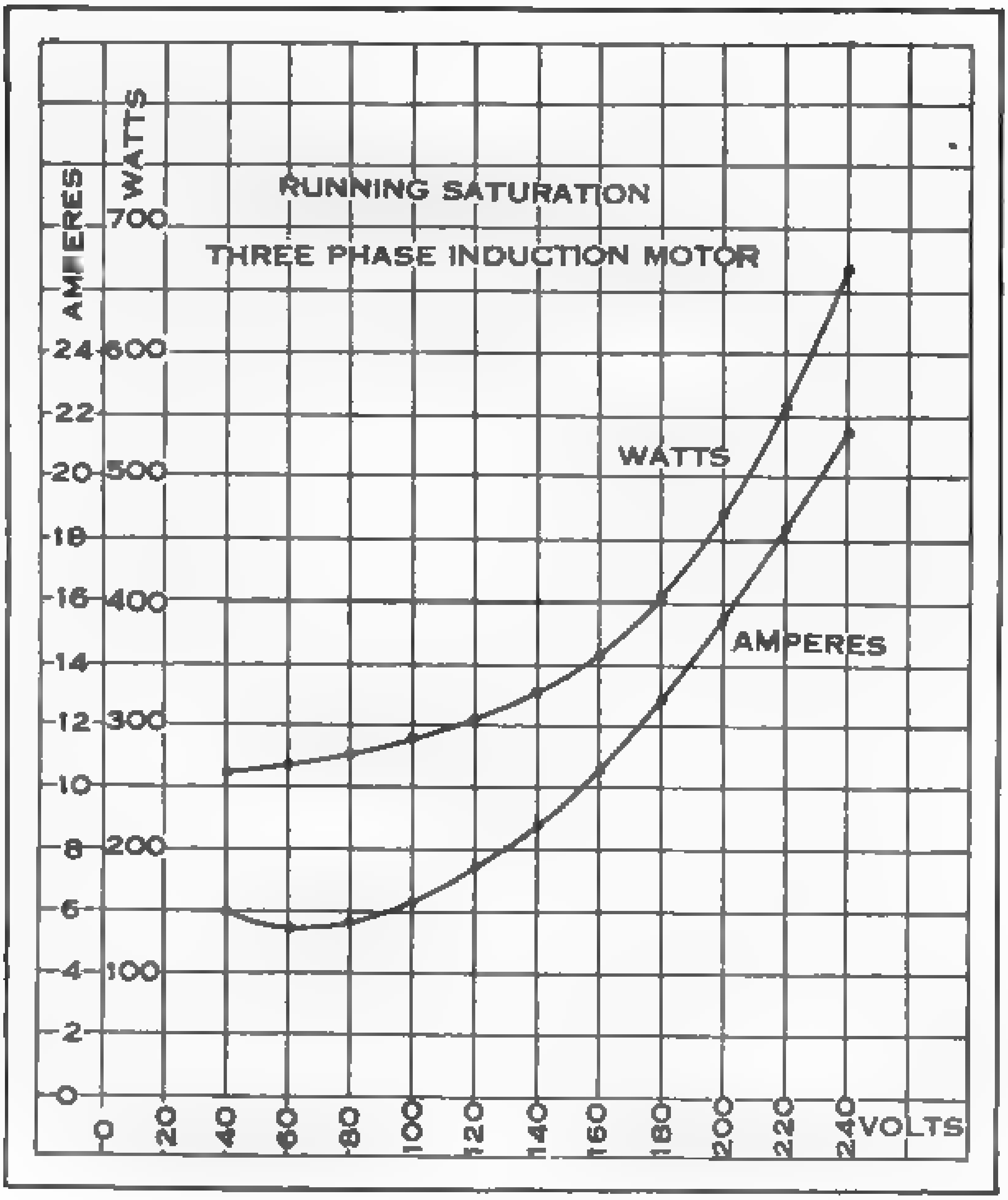


FIG. 886.—Current and power curves for three-phase induction motor while running.

voltage and decreasing in steps of about 10% (taking one reading at exactly normal voltage) until the speed "breaks" and plotting the results in curves will be most satisfactory, as the curves eliminate all chance of erratic values at normal voltage. If the

motor has a wound rotor, the rotor windings should be short circuited at the rings. The correctness of the results obtained in this test determine largely the accuracy of the diagram and great care must be taken in getting the no load losses. Curves are then

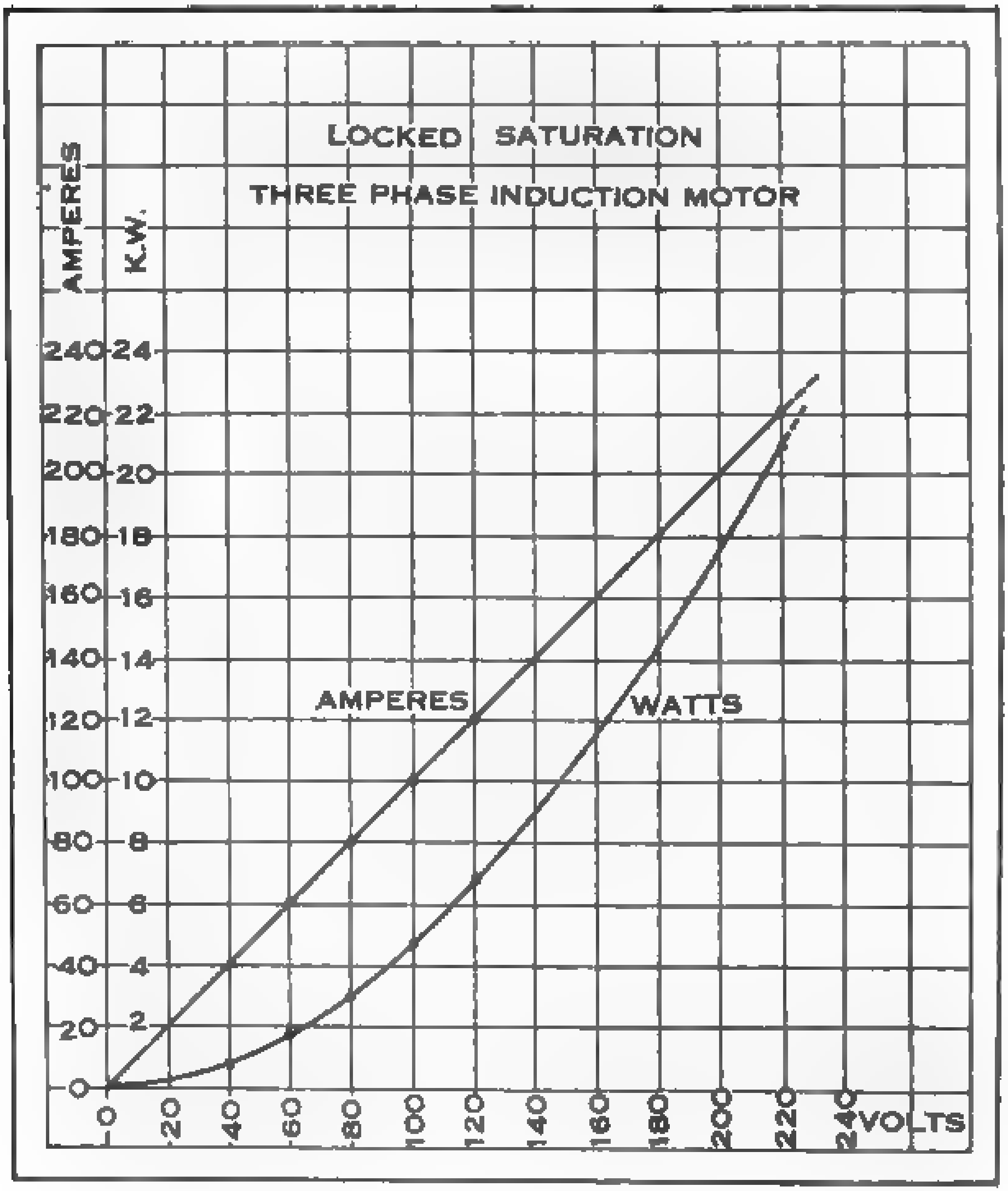


Fig. 887.—Current and power curves for three-phase induction motor while locked.

plotted as in Fig 886, using terminal volts as abscissas and equivalent single-phase amperes as ordinates for one curve and terminal volts as abscissas with total watts as ordinates for the other. This constitutes the **running saturation test.**

Next block the motor's rotor by a brake or bar and, beginning at about 50% normal voltage, read the total watts, volts across terminals and amperes per terminal. Repeat the operation, decreasing the applied voltage in even steps to zero, so as to obtain at least 5 or 6 readings. Two curves are plotted from these values as in Fig. 887, one using terminal volts as abscissas and equivalent single-phase amperes as ordinates, the other using terminal volts as abscissas and total watts as ordinates. If the current is not the same in all phases for any step, the average amperes are used in computing the equivalent single

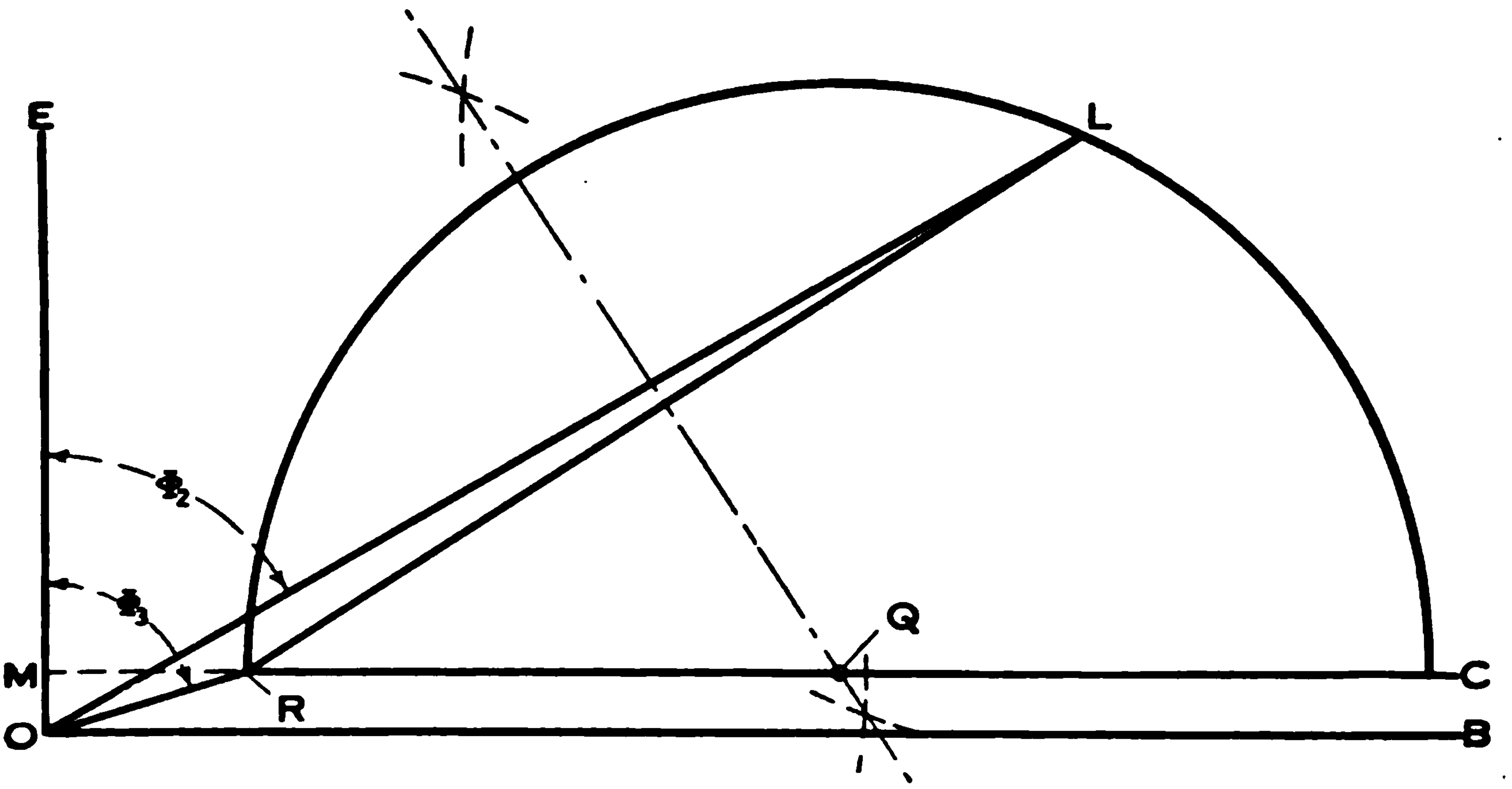


FIG. 888.

phase amperes. These curves should be projected by calculation or graphically to normal voltage values, bearing in mind that the current varies directly with the voltage, and the watts as the square of the voltage. The watt curve may be determined logarithmically as it is a section of a true parabola. This constitutes the **locked saturation test,** and judgment must be used as to the maximum voltage applied to prevent burning up the motor.

Next, measure the terminal resistance of the motor stator between all terminals and average. If the rotor is of the wound type, measure its resistance at the rings in the same way. Reduce all resistance readings to the **equivalent single-phase resistance** by dividing by two.

Construction of the Diagram.—Referring to Fig. 888, lay off two lines *OE* and *OB* at right angles to each other. Lay off *OR* to a convenient scale representing the no-load amperes in the

stator (equivalent single-phase values) and at such an angle to OE that cos Φ_2 is equal to the no-load power factor.

Lay off (to the same current scale) line OL at an angle Φ_2 representing the stator current and its phase angle with the rotor locked, at normal voltage. Lay off the line RC through R parallel to OB and connect R and L by a straight line.

RL represents the current in the rotor with the rotor locked, being the vector difference between OR, the no load stator current and OL, the locked stator current. Bisect RL and continue bisector to cut line RC. This intersection at Q will be the center of the circle between the circumference of which and R, lines may

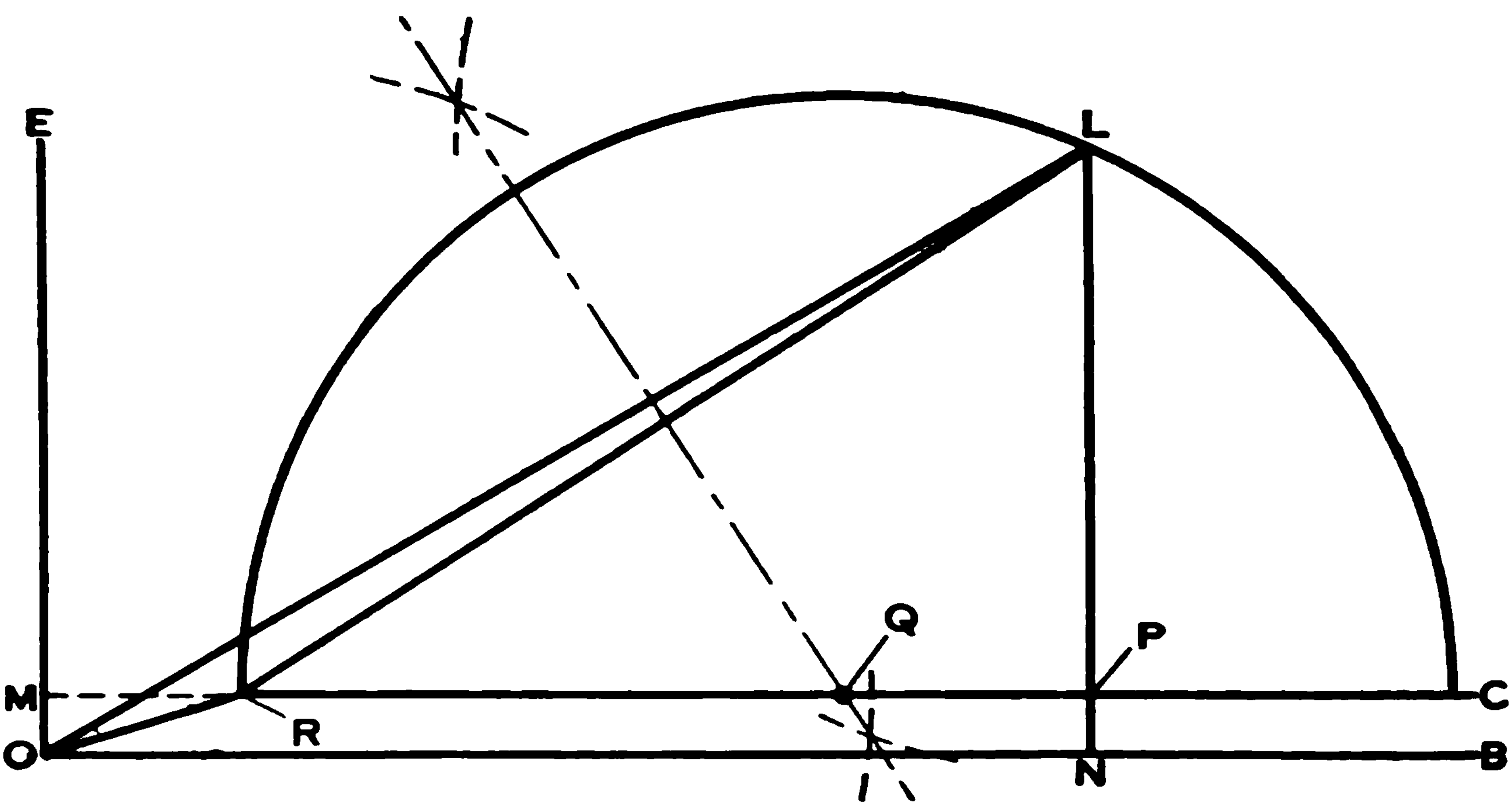


FIG. 889.

be drawn, representing the rotor amperes at any load. Draw this circle as shown in Fig. 888.

When the motor is running idle, the power consumed is shown by the line OM, Fig. 889, which is the energy component of the no-load current OR. This power is simply that required to overcome the losses due to friction, windage, hysteresis, eddy currents and a small stator copper loss. Since the motor is running at practically synchronous speed, there is no variation of flux in the rotor iron and consequently no voltage or current in the rotor windings. Since there is no flux variation, there is practically no iron loss in the rotor at no load.

When the rotor is locked, the frequency of the rotor currents is that of the line and the flux in the rotor reverses with the frequency

of the supply. This flux variation produces a loss due to hysteresis and eddy currents in the rotor which is added to the no-load loss. At the same time the friction and windage have become zero since rotation has ceased. It may thus be seen that as the friction and windage decrease with the load, the iron losses in the rotor increase, tending to maintain the no-load losses, OM, constant. This is so nearly true that it is the custom to assume that OM is constant in value for all loads and speeds. Since MC, Fig. 889, is parallel to OB, NP is also equal to these constant losses.

When the rotor is locked, there is no speed and consequently no output. It is obvious that under this condition all of the power input to the motor must be lost within the machine itself. As

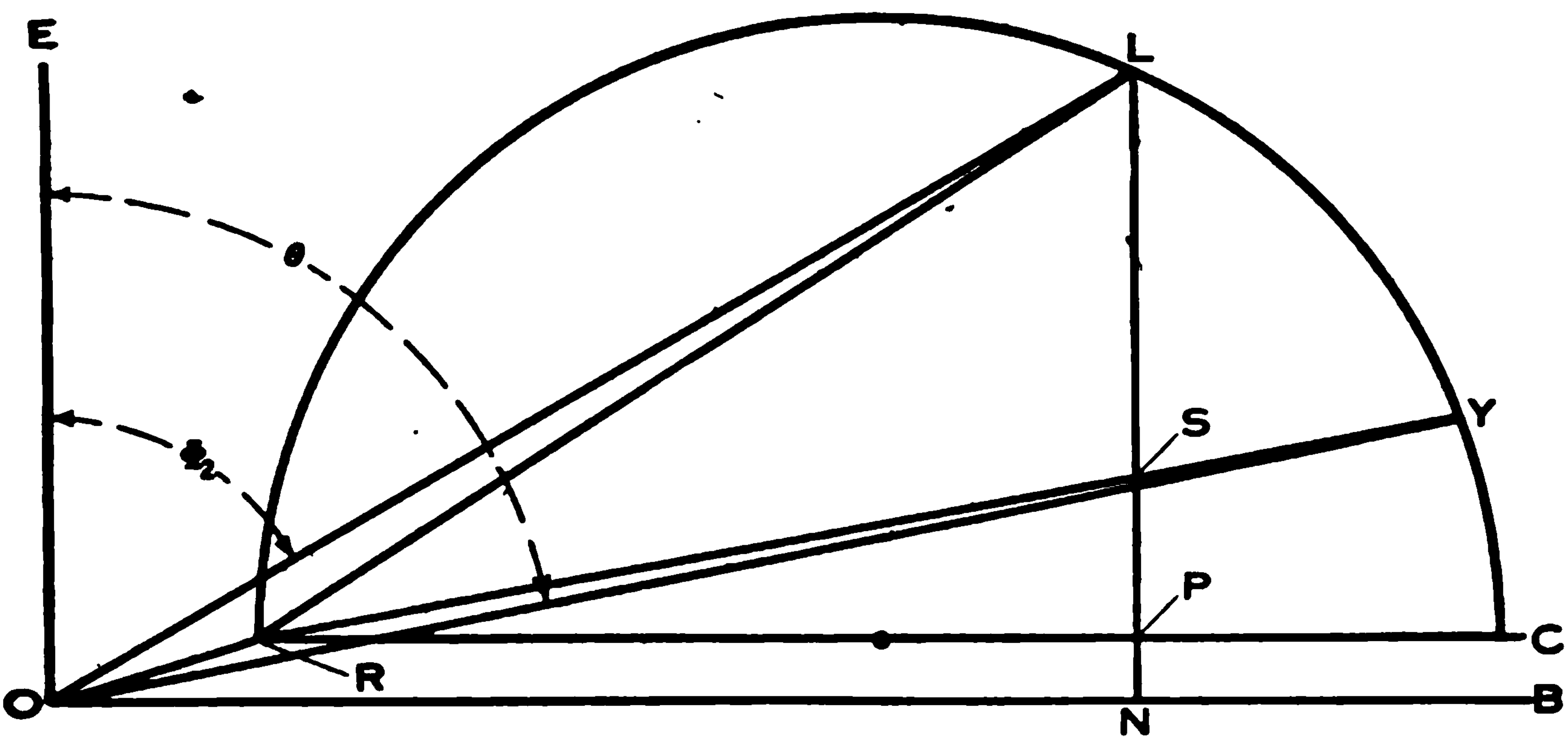


FIG. 890.

OL, Fig. 889, represents the current input to the motor, the line NL must represent the energy component of that current, since it is parallel to OE. Then the line NL is proportional to the power input to the machine and also to the power lost in the machine when the rotor is locked and normal voltage applied at the terminals of the stator. Now the power lost in an induction motor is composed of three parts, that lost in the stator copper, that lost in the rotor copper and the constant loss mentioned above. Then the line NL may be divided so as to represent these three losses.

Since NP, Fig. 890, is the constant loss, PL must represent the copper losses of the rotor and stator combined. It is possible to determine the location of a point S so as to divide the line NL into two parts where PS represents the stator copper loss and SL the

rotor copper loss. The point S may be found by one of the three following methods:

If the motor has a wound rotor, then,

$$\text{Rotor resistance} : \text{Stator resistance} :: SL : PS \qquad (11)$$

Or, if the motor has a cage rotor, the point S may be located as follows:

The energy component of the stator current in amperes is obviously equal to the watts lost in the stator divided by the rated voltage. Since the stator current squared, multiplied by the stator resistance equals the watts lost and both of these values are known, the following formula may be applied:

$$\frac{(O\text{-}L)^2 \times \text{Stator resistance}}{\text{Rated voltage}} = SP, \qquad (12)$$

which is the energy component of the stator current.

Still another method may be used which is called the "cotangent method."

The line ON, Fig. 890, represents the reactive component of the stator and rotor current with the rotor locked and, for the current OL, is proportional to $X_1 + X_2$, where X_1 is the reactance of the stator and X_2 is the reactance of the rotor. This is the combined reactance of the stator and rotor because the phase angle of the current OL depends on the reactance of both, the lag of the rotor current being transferred into the stator by the magnetic linkage between the two. The energy component of OL is represented by the line NL, as has been stated. Wherever the point S may be, it is evident that the line NS represents the total energy loss in the stator. The part of NS as shown by NP has already been accounted for as being representative of the constant losses, leaving PS as being proportional to the stator copper loss. Then the line PS represents the energy component of OL, which may be attributed directly to the stator resistance.

It is obvious now that the ratio of the energy component of the stator current to the reactive component is the cotangent of the angle θ. If the cotangent is known, the angle θ may be found and, knowing this angle, the line OY may be drawn terminating at Y, which represents the current which would flow in the stator with the rotor locked, and normal voltage applied, if the rotor had zero resistance, but with stator resistance and stator and rotor reactance remaining unchanged.

The semicircle *RLYC* is the path of the current locus of stator current as well as rotor current. Since the value of the line *PS*, representing the stator copper loss, is dependent on the "added current"—that is, the current drawn over and above that at no-load—the point *S* must be located by a line within the semicircle. Then if a line is drawn connecting *R* and *Y*, the point *S* where it intersects the line *PL* will be the desired dividing line between the stator and rotor copper losses.

The cotangent of the angle θ may be found as follows:

$$X_1 + X_2 = \frac{E \sin \Phi_2}{OL}$$

because the combined reactance of the stator and rotor is equal to the reactive voltage divided by the current, and *E* (the normal voltage) multiplied by the sine of the angle Φ_2 is this reactive voltage.

If *R* is used to denote the stator resistance, then

$$\text{Cot } \theta = \frac{R}{X_1 + X_2},$$

as shown by the preceding discussion.

Substituting the value of $X_1 + X_2$, as first found, in this equation we have:

$$\text{Cot } \theta = \frac{R \times OL}{E \sin \Phi_2} \tag{13}$$

Having thus found the cotangent of θ, the angle itself may be ascertained from a table. The line *OY* may now be constructed, diverging from the line *OE*, by the angle θ.

As will be stated later, the values measured vertically between the line *R Y* and the semicircle represent the energy component of the current input into the rotor. This is also proportional to the torque, as will be shown and for this reason this line *RY* is known as the **torque line**. Since the stator and rotor losses will always bear the same relation to each other regardless of the load, the vertical values between line *RY* and line *RL* represent the rotor copper loss and those between line *RY* and line *RC* the stator copper loss for any value of current between no load and locked values.

It should be mentioned that the point S cannot be located exactly by any of these methods, but that they are sufficiently accurate for the great majority of cases, the error introduced being so small as to be negligible. In motors where the no-load current is a considerable proportion of the full-load current some modification of this diagram is necessary.

The diagram, Fig. 890, is now complete and may be analyzed. Since the line OE represents in direction, the applied voltage, it follows that all values measured vertically (parallel to OE) are energy values and all those measures horizontally (parallel to OB) represent wattless values.

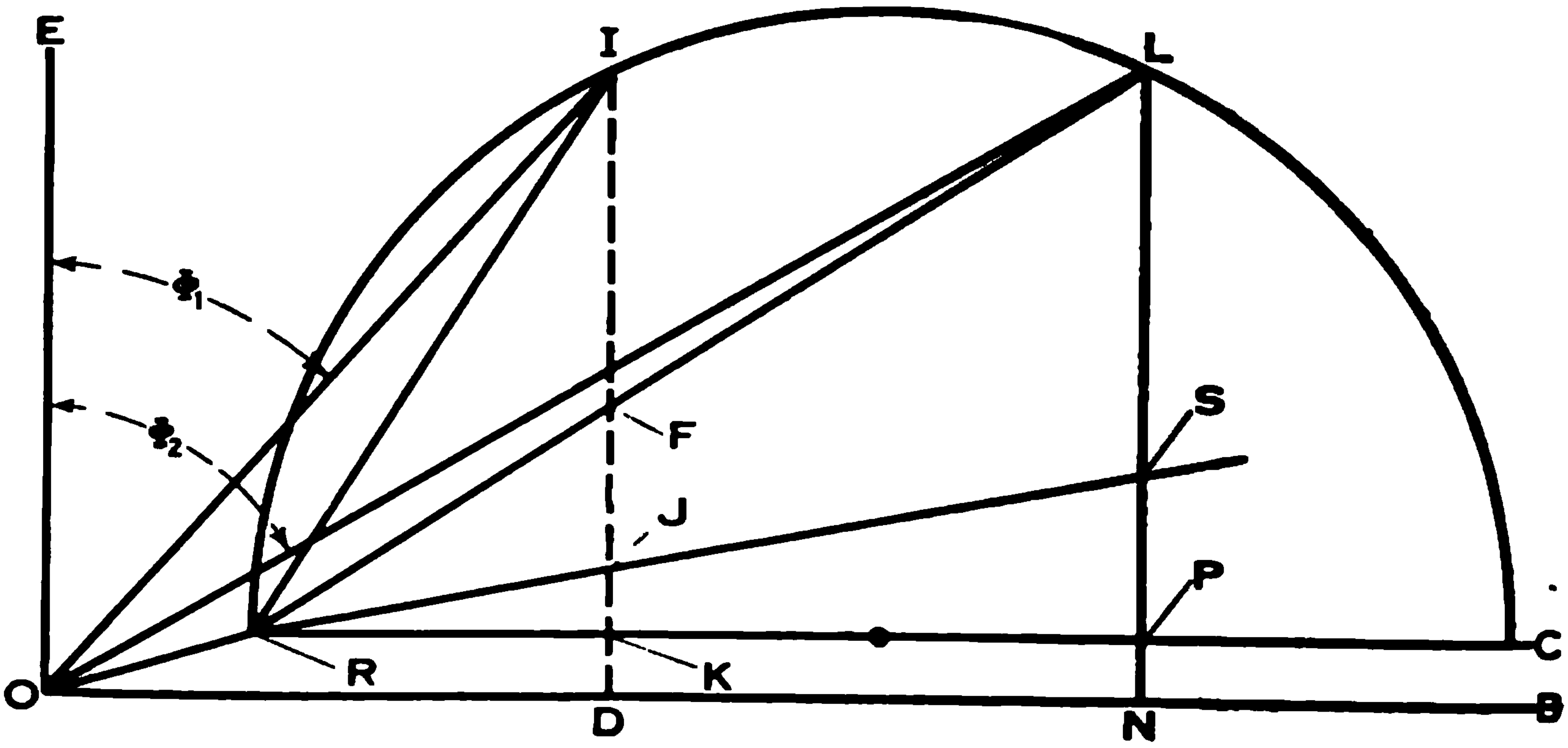


FIG. 891.

Selecting the equivalent single-phase current OI, Fig. 891, which would be required for full load, a vertical line as DI is drawn from D to I. It is obvious that line DK will represent the constant losses. As has been stated, the line KF will represent the combined rotor and stator losses for this value of current and JF represents the rotor loss. Then DF represents the total losses for full load and DI the input. Consequently, the output must be the difference between these two values or FI. If FI is the output and DI the input, then

$$\frac{FI}{DI} \times 100 = \text{the full-load efficiency in per cent.}$$

As OI represents the stator current, in phase direction as well as in value, the angle Φ_1 must be of such a value that its cosine is the full-load power factor.

Since the slip, as expressed in per cent, is the ratio of the rotor losses to the power input to the rotor,

$$\frac{JF}{JI} \times 100 = \text{per cent slip at full load.}$$

Then 100, minus the per cent slip, equals the per cent of synchronous speed at which the motor runs at full load. The synchronous speed as calculated from the number of poles of the motor and the frequency of supply, multiplied by the per cent of synchronous speed, is the actual speed at full load. The power factor for any load may be determined by obtaining the cosine of the angle between the stator current line OI and the reference line OE. This value may be obtained from any set of trigonometric tables.

The output of a motor may be expressed by the following formula:

$$\frac{n \times T}{5252} = \text{H. P.} = \frac{P}{746}$$

Where:

n = r.p.m.
T = torque in pound-feet.
P = watts.

By transposition the formula becomes:

$$T = \frac{P}{n \times 746} \times 5252 = \frac{P}{n} \times 7.04 \text{ and } \frac{T \times n}{7.04} = P.$$

Now JI, Fig. 891, in amperes multiplied by the rated voltage, gives the watts input to the rotor. If the rotor ran at synchronous speed, the torque would be found by substituting these values in the above equation. The watts input to the rotor is sometimes called "synchronous watts," which is a term used to express the output of the machine if it ran at synchronous speed instead of actual speed, the torque remaining the same. Thus if the torque of a motor is known, this value, multiplied by the known synchronous speed and divided by 7.04, will give the synchronous watts or power input to the rotor.

It is apparent then that, for any load, the torque of a motor is proportional to the line JI. Now the line JI, Fig. 891-A, will be a maximum when it is drawn from a point marked "maximum

torque" on the circle which is touched by a tangent drawn parallel to line *RS*. This point fixes the pull-out or maximum torque point of the motor.

Since the output of the motor is proportional to the line *FI* it is evident that this line will have its maximum length when drawn from a point marked "maximum output," in the circle touched by a tangent drawn parallel to line *RL*. This point will evidently be the point of maximum output.

Maximum power-factor will occur at such a load that the line *OI*, which represents the stator current, lies tangent to the circle

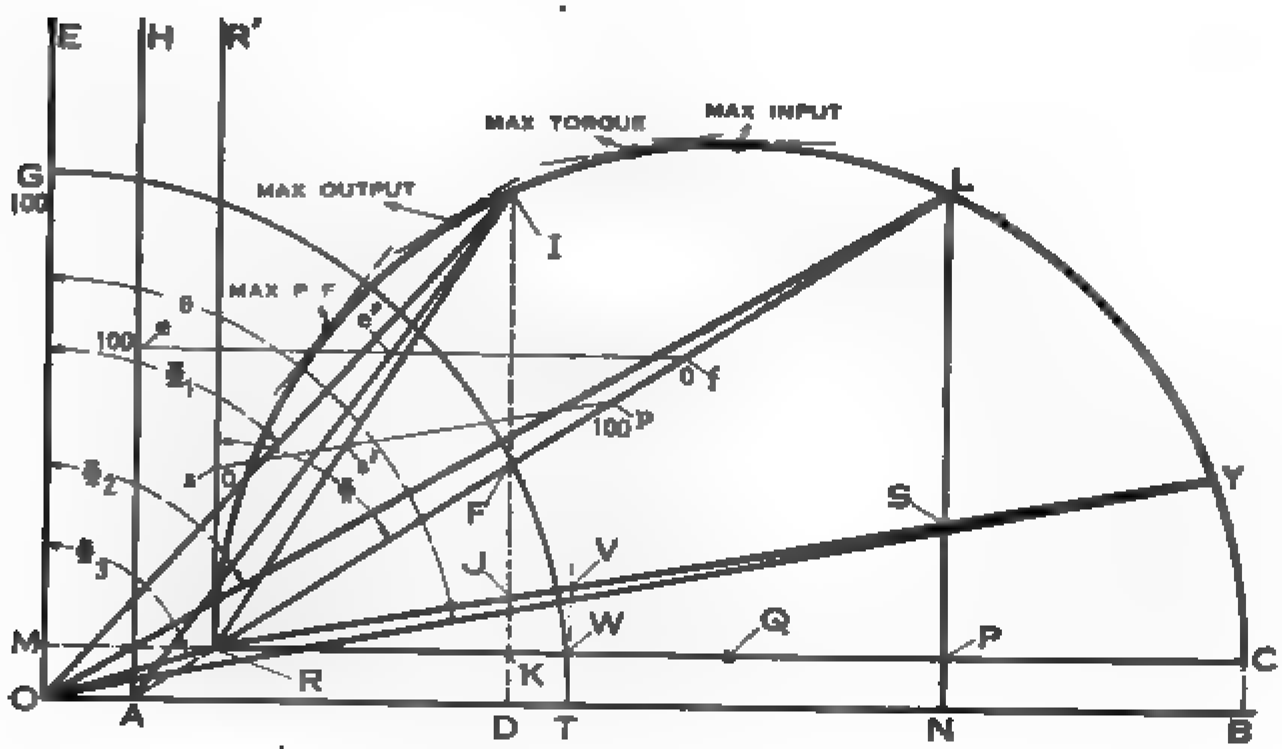


FIG. 891-A.

as, at this point marked "maximum power factor," the angle Φ_1 is a minimum.

Since the line *DI* is proportional to the input, maximum input will occur when *I* is at the point in the circle marked "maximum input," touched by a tangent drawn parallel to *RC*.

From the foregoing it will appear evident that the performance of the motor may be determined for any value of load and stator current.

The motor's performance may be more easily analyzed by the diagram shown in Fig. 891-A, which is more complete than Fig. 891, in that lines have been added for the graphic determination of power factor, efficiency and slip.

Using O as a center, draw the power-factor quadrant GT with a radius of 100 units and divide OG into 100 equal parts. Extend RL back to A and erect a line AH at that point parallel to OE.

Now draw a line sp, anywhere in the diagram between RR' and RL, but parallel to RS, in such a position that it may be conveniently divided into 100 equal parts. This will be called the "slip line."

It has been stated that the per cent slip for a given load is equal to $\frac{JF}{JI} \times 100$. If a line is drawn between RL and RR' (which is a line erected perpendicular to RC at R), and parallel to line RY, and this line intersected by another straight line drawn from K to I, it can be proven that the point of intersection divides this first line into two parts one of which is proportional to the slip, the other to the per cent synchronous speed and the whole line to the synchronous speed. Such a line is shown in Fig. 891-A as sp. This line, which is called the "slip line," need not be any given length, so it is usual to select some value that is easily divisible into 100 equal parts, the only requisites being that it extend from line RR' to RL, and that it be parallel to line RY. An easy method of locating this line is to select the desired value for the length and then slide the scale along the diagram, keeping it always parallel to RY, until the required location is found. Numerals designating the divisions (0 to 100) are placed on this line with the zero value at the point where ss' intercepts line RR'.

If now the line RI is drawn, intersecting sp as at s', it only remains to be proven that the following proportion is true, to show that the numeral at the intersecting point s' is the slip in per cent.

$$ss' : sp :: JF : JI$$

This is true, because triangles FRJ and Rsp are similar, as are also triangles RIJ and $s'sR$.

This similarity may be shown as follows:

$$JF : Rs :: RJ : sp \text{ and } Rs : JI :: s's : RJ$$

$$\text{and} \quad \frac{JF}{Rs} = \frac{RJ}{sp} \quad \text{also} \quad \frac{Rs}{JI} = \frac{s's}{RJ}$$

Combining these two equations, we have:

$$\frac{JF}{Rs} \times \frac{Rs}{JI} = \frac{RJ}{sp} \times \frac{s's}{RJ}$$

By cancellation:

$$\frac{JF}{JI} = \frac{s's}{sp}$$

Since $\frac{JF}{JI} \times 100$ equals the per cent slip, then $\frac{s's}{sp} \times 100$ also equals the per cent slip.

As the line sp is 100 units long,

$$\text{the per cent slip} = \frac{s's}{100} \times 100 = s's.$$

It has been shown that $\frac{FI}{DI} \times 100$ equals the per cent efficiency. If now some line may be drawn which may be divided graphically in the same ratio as FI to DI, the efficiency may be determined as readily as the slip.

If the line RL is extended back to cut the line OB, as at A, and a perpendicular as AH erected at that point, a line ef may be drawn between AH and RL, parallel to RC. This line may be to any convenient scale which is easily divisible into 100 equal parts. It may be located, as was the slip line, by first selecting some suitable scale and sliding the scale along the diagram until the proper location is reached, keeping it always parallel to OB.

If now a line is drawn connecting A and I it will intersect line ef at some point as e'. We now have two similar triangles, ADF and Aef. Triangles AID and $e'Ae$ are also similar.

It then follows that:

$$DF : Ae :: AD : ef \quad \text{and} \quad DI : Ae :: AD : e'e$$

$$\text{then} \quad \frac{DF}{Ae} \times \frac{Ae}{DI} = \frac{AD}{ef} \times \frac{e'e}{AD} \quad \text{and} \quad \frac{DF}{DI} = \frac{e'e}{ef}. \tag{14}$$

Since,

$$\frac{DI}{DI} = \frac{ef}{ef} \tag{15}$$

subtracting (14) from (15)

$$\frac{(DI) - (DF)}{(DI)} = \frac{(ef) - (e'e)}{(ef)}$$

from the diagram, $(DI) - (DF) = FI$ and $(ef) - (e'e) = e'f$.

Then by substitution,

$$\frac{FI}{DI} = \frac{e'f}{ef}$$

Since $\frac{FI}{DI} \times 100$ equals the per cent efficiency, $\frac{e'f}{ef} \times 100$ also equals the efficiency.

The line *ef*, being 100 units long, numerals should be placed on the line designating these units with the zero value at *f*. Then

$$\frac{e'f}{100} \times 100 = e'f$$

which is the efficiency in per cent.

From the above formulas and diagram, the efficiency, torque, slip, power factor and primary and secondary amperes for any load may be found as well as the ratios between them, with an accuracy well within commercial limits.

For motors under 5 horse power this diagram is not accurate, and for motors under 50 horse power the Specht and some other diagram, which tilt the base line of the circle, are somewhat more correct. Above 50 horse power, this diagram, based on the McAllister diagram, is about as satisfactory as any, and forms the basis of practically all similar graphic solutions.

SECTION XVI CHAPTER VII

ALTERNATING-CURRENT MOTORS

THE CIRCLE DIAGRAM

1. Explain the method of performing the three tests required and state data obtained from each, that will be used in drawing a circle diagram for an induction motor.

2. Sketch a circle diagram and designate the lines which indicate the following quantities:

(*a*) No load stator current.
(*b*) Locked stator current.
(*c*) Current locus.
(*d*) Output of motor at some load point.
(*e*) Rotor copper losses.
(*f*) Stator copper losses.
(*g*) Motor constant losses (or stray power).
(*h*) Efficiency of motor.
(*i*) Torque of motor.

SPECIAL A. C. GENERATORS

INDUCTION GENERATORS

As already explained, the synchronous generator must run in exact synchronism with all generators with which it is connected in parallel and with all motors of the same type which it supplies.

The induction generator does not need to run in synchronism with other machines with which it is connected in parallel or with its load. It is simply an induction motor driven mechanically at a speed above synchronism. Its output depends solely upon its speed above synchronism. The possibility of so operating this machine has been known for a number of years, but only comparatively recently has the industry developed so as to warrant its introduction on a large scale. In certain circumstances it is now preferable to the synchronous generator.

The stators, or stationary members of both types of alternator, are usually identical in construction. This structure carries the armature winding of the generator, which is usually polyphase in character. The electro-motive-force generated in this winding is induced by a revolving magnetic field internally located.

The chief difference between the two types of machines is in the revolving member, or rotor. In the synchronous machine the field structure has clearly defined magnetic poles excited by direct current supplied through slip rings at 110 or 220 volts.

The field structure of the induction generator contains a short-circuited winding, the same as that found on the rotor of an induction motor. The magnetic field in these two types of machines is produced in distinctly different ways. In the synchronous generator, as explained above, it is brought about by the direct action of continuous current in the field coils. But in the induction generator the field is produced by the very alternating current which flows in the stator winding. This current, by its reaction, induces current in the rotor, which in turn produces the magnetic field upon which the generator depends for its electro-motive-force.

As is well known, the fixed position of the field poles of the synchronous generator necessitate its running in step with the alternating system to which it is connected. This means that the revolving member of every synchronous machine connected to the same system must move forward exactly one pole for every reversal of voltage in the system.

The induction generator cannot run in synchronism with the system to which it is connected, but must always run faster, otherwise there can be no reaction of the current issuing from the stator winding upon the rotor. And this reaction is necessary in order that current may be induced in the stator. The greater the load this machine is expected to carry, the greater the amount by which it must exceed synchronism.

Because of the flexibility in speed of the induction generator, the possibilities of "hunting," which are always more or less objectionable in synchronous systems, cannot occur with this machine.

These two machines perform in widely different ways because of the difference in the manner of producing their magnetic fields. In the synchronous generator the electro-motive-force induced in its armature winding depends directly upon the amount of current supplied to its field winding. The load upon the machine does not appreciably effect this voltage; that is, the only variation in voltage is due to the regulation of the machine, which falls slightly as the output and power factor fall.

But, as stated, the induction generator field is produced by the reaction of the currents issuing from the machine. This fact results in a remarkable condition. The induction generator has no regulation and no magnetic field of its own, save the voltage which is maintained at its terminals, and the load. The magnetic field in this machine is produced by the armature reaction of its own stator currents, and the value of these currents, as well as the voltage produced, depends upon the electro-motive-force maintained at the induction generator's terminals. Now the only way that this voltage can be maintained is by connecting some other synchronous machine in parallel with the induction generator's terminals. The magnetic field of the induction generator then becomes dependent upon the voltage of the synchronous machine connected therewith, and the latter machine's voltage depends upon its excitation from its own direct-current

exciter. The induction generator, therefore, cannot operate by itself at all. It will deliver no power unless it is connected in parallel with synchronous apparatus. Rotary converters, synchronous motors or other synchronous generators will answer, but it is important to note that the machine has no voltage of its own and can furnish no power unless so connected.

Because of the induction generator's lack of regulation, the regulation of a combined system of synchronous and induction generators will be the regulation of the synchronous machines in circuit. If the load changes on the system, the voltage will

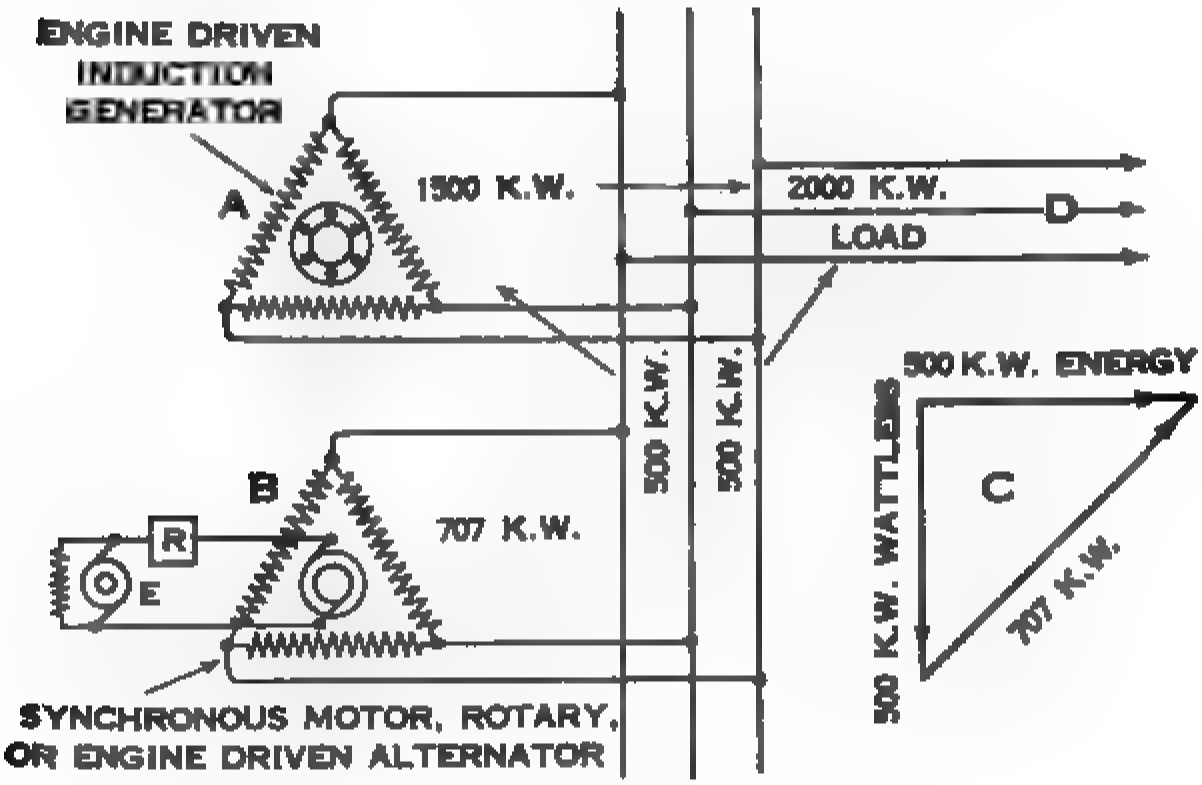


Fig 892.—Induction generator operating in parallel with synchronous apparatus.

vary in proportion to the change on the synchronous machines as though they alone were in circuit.

Fig. 892 represents a 1,500-kilowatt induction generator *A*, driven by an engine. This machine has a cage-wound rotor and is in every sense like a three-phase induction motor. It is connected to the bus bars, across which there is also connected a synchronous generator *B*. This machine is also engine driven and excited with direct current in its revolving field from an external exciter *E*. This synchronous machine will operate to the best advantage if it has a rating of 707 K.V.A. and 500 K.W. at 71% power factor. Then, as shown at *C*, it would be capable

of furnishing 500 real kilowatts of energy to the load and also 500 apparent kilowatts of wattless lagging current for the excitation of the induction generator *A*. While this current for the load and the excitation of the induction generator lags with respect to its source, it leads with respect to the voltage of the induction generator. A 2,000-kilowatt load located at *D* would now derive its power jointly from the two generators in parallel, 500 kilowatts from the synchronous machine and 1,500 kilowatts from the induction machine. At the same time the synchronous machine would furnish the induction machine with 500 kilowatts lagging current required for its excitation. One of the peculiar features of an induction generator is that it requires that there shall be available, in parallel with it, synchronous apparatus of at least 30% of its kilowatt rating for excitation purposes. The bulk of the real power for the load comes from the induction generator.

The induction generator, then, is a machine which may be floated upon a synchronous system and will supply real power to the system without having anything whatever to do with the voltage regulation or control.

If the external circuit on a synchronous machine is opened, it still produces its normal voltage, but if the external circuit on an induction generator is opened, it ceases to generate entirely and produces no electro-motive-force at its terminals.

If a synchronous generator is short circuited, the armature winding still continues to generate an electro-motive-force, because the magnetic field is independent of the e.m.f. and is maintained by direct current. It is thus possible for a synchronous generator to deliver on short circuit many times its full-load current, as the entire electro-motive-force is consumed in forcing this current through a negligible resistance. The magnetic reactions, as well as the heating effect of such currents, may be disastrous to the machine.

But as the induction generator, when short circuited, has no voltage at its terminals, and can therefore receive no exciting current, it will possess no magnetic field and will therefore cease to generate. When such a machine is short circuited the current will gradually fall from what the machine was delivering to zero, at a rate depending upon the impedance of the internal circuit, as would be the case with current in any choke coil when the voltage of supply was withdrawn.

It is interesting to note that the total current which a system, consisting of synchronous and induction generators in parallel, may furnish on short circuit, is limited to the maximum possible short-circuit current of the synchronous generators alone.

A synchronous generator can produce currents with leading or lagging components as well as true energy—that is, it can supply the so-called wattless currents, the value of which depends upon the nature of the load to which it is connected.

The induction generator can produce nothing but true energy currents, but at the same time it consumes continuously a wattless lagging current required to excite its field. This latter current is drawn from any synchronous apparatus with which it is connected in parallel.

It is evident from the foregoing that an induction generator cannot supply a system with alternating current by itself if the system requires current for light and power. This would involve wattless lagging currents, as well as true energy currents. It must therefore be used in combination with synchronous generators. Then all of the lagging current for the system would be carried by the synchronous generators, as well as the lagging current which the induction generator itself required for excitation.

If a city has a load calling for a considerable lagging current, it is not wise to supply a very large percentage of induction generator capacity because the synchronous generators have to supply all the lagging current and they may be overloaded thereby.

The induction generator has its greatest advantage on a system requiring no lagging current, as in the case of rotary converters, operated exclusively on large power stations, for such a system would be run at 100% power factor and the rotary converters could thus be made to supply the exciting current for the induction generators.

A good distinction between these two types of machines may be made by saying that the **synchronous machine generates electric current** while the **induction machine generates electric power.** That is, a synchronous generator may supply current to a system whether the current called for is a powerless current or a real power current. The induction generator, however, can supply only current of real power value, and no wattless current.

An induction generator is, therefore, the ideal machine for converting mechanical energy into electrical energy. It consumes mechanical power and transforms the same into electrical power. It is not dependent upon separate field excitation, speed, synchronizing or any other feature.

It is, therefore, the ideal machine to float on an alternating system. It will absorb mechanical power and change it into electrical power in direct proportion to the amount absorbed. Moreover, it will deliver this power at whatever voltage the system happens to run on, and at any speed. It requires only that the machine be driven just above that for which the system is set by its frequency. It involves no regulation, and represents the ideal method for converting one kind of energy into another.

Phase Advancers

In 1914 a new type of machine, called a phase advancer, was devised for improving the power factor of induction motors.

The magnetizing field for a synchronous motor is produced by a continuous current circulating in a winding on a rotating structure with definitely placed magnetic poles. By supplying the structure with more ampere-turns than are necessary for the production of the magnetic field in a machine of given size, it is possible to produce a leading current in the stator winding. This will compensate for lagging current in other parts of the system. A high-power factor may thus be obtained, and with large synchronous apparatus even a leading current may be brought about on the entire system.

The phase advancer bears the same relation to an induction motor that a direct-current exciter does to a synchronous motor. But in the induction motor it is not possible to use a continuous direct-current generator for magnetizing purposes, because the rotor winding slips behind the rotating field of force when a load is applied. It is, therefore, necessary to supply this winding with polyphase currents of a low frequency which will always correspond to the slip of the induction motor.

As usually constructed, the phase advancer consists of a direct-current drum armature with a commutator. On the commutator are placed three sets of brush holders for every pair of poles, located, with respect to each other, 120 electrical degrees art. The stationary member is merely a frame containing an

assembly of laminations external to the armature but without windings.

This device is direct connected to a small cage-wound induction motor. The power required to drive it is only that necessary to supply the hysteresis and friction losses. This amounts to only about 1 horse power for a 500-horse power, 2,200-volt

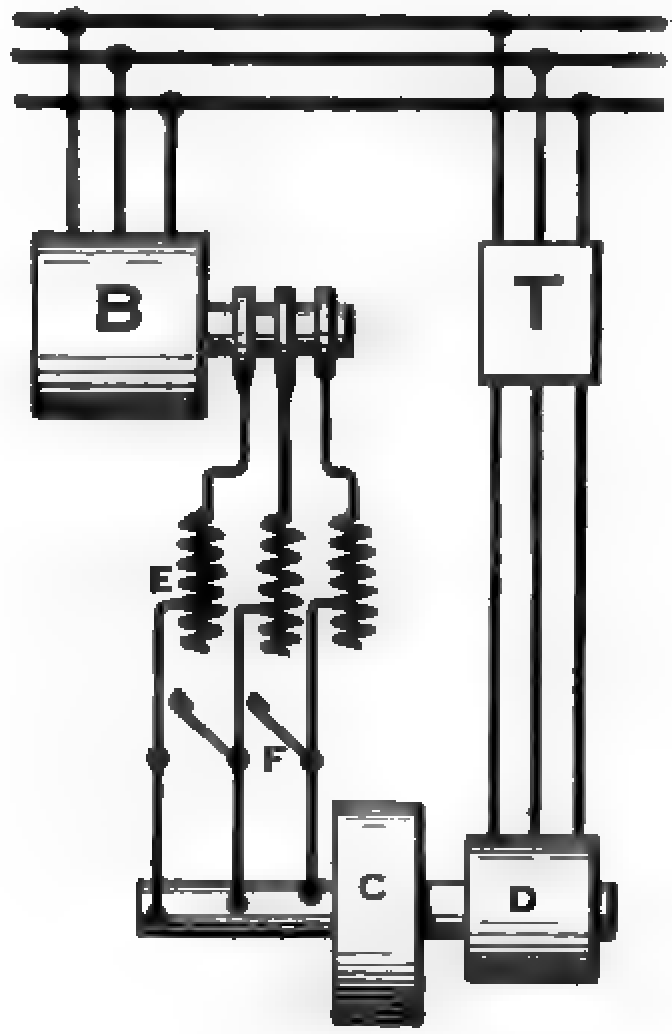


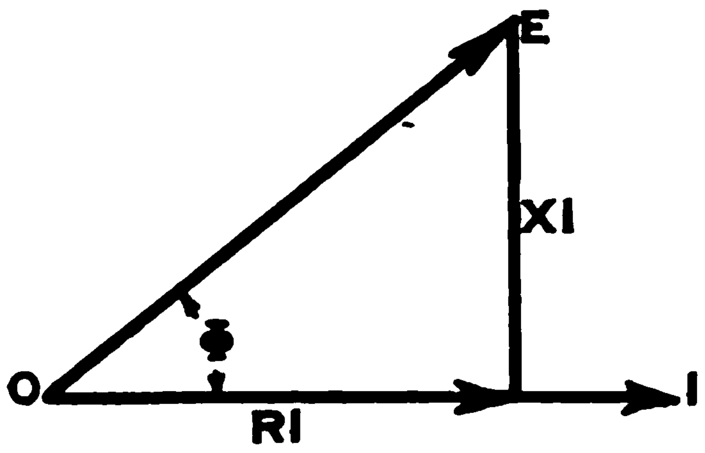
FIG. 893.—"Phase advancer" for improving power factor in induction motor.

machine. The copper losses are supplied by the rotor of the large induction motor.

Fig. 893 represents the arrangement of apparatus and winding for the outfit. B is the main induction motor with a form-wound rotor and three slip rings; C is the phase advancer connected to its driving motor D; E is a controlling device with resistance for starting; F is a short-circuiting switch; T represents a transformer if the source of supply is of high voltage. The switch F is employed to short-circuit the phase advancer when the motor B is starting. The controller E is employed for acceleration. After the motor is up to speed, the switch F is opened.

To understand the operation of this device, suppose that the phase advancer is stationary and is receiving current at slip frequency from the rotor circuit of the main motor *B*. Under these conditions, the phase advancer behaves like a three-phase reactance, the current circulating in its winding producing a rotating field, which revolves in space at a speed corresponding to the frequency of the currents supplied from the slip rings.

If, now, the phase advancer is driven by the motor *D* in the same direction as that in which the rotating field of force therein was traveling, the speed of rotation of that field in space will remain unchanged, because it is independent of the speed of rotation of the armature. This is because the points at which the alternating currents are led into the windings are fixed in



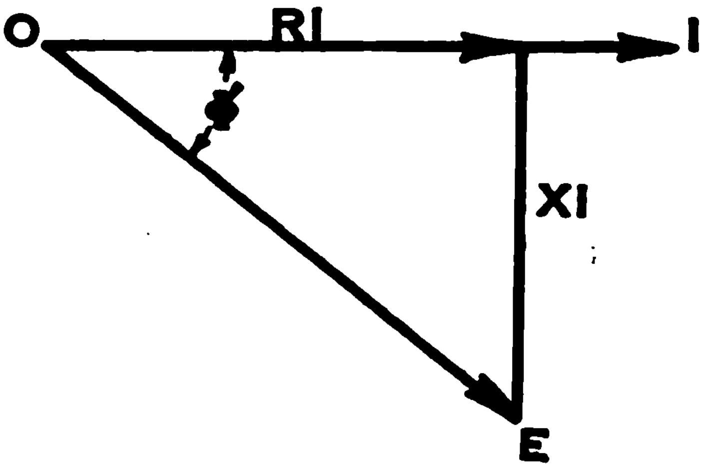


FIG. 894. FIG. 895. FIG. 896.

space. The result is that, when the armature is driven in the direction in which the field was traveling and at a speed corresponding to the speed of the field, the relative motion of the field and the armature become zero. This results in the disappearance of the choking effect of the three-phase reactance, and the current in the rotor circuit of the main motor *B* comes into phase with the e.m.f. generated therein. Consider the vector in Fig. 894, where *O-E* represents the phase e.m.f. at the brushes of the phase advancer and the current *O-I* the amperes fed to each branch. Here *R-I* is the component to overcome the e.m.f. produced by the revolving field—that is, the e.m.f. of self-induction. When the rotor has been brought up to the speed of the rotating field and has overtaken it, this reactance disappears and the impressed e.m.f. *O-E* comes into phase with the current *O-I* as in Fig. 895.

If now the armature is driven at a still higher speed than that of the revolving field, the original lagging current and what subsequently became a current in phase with the e.m.f. will now actually become a current which will lead the e.m.f. This is shown in Fig. 896, where *O-I* is the current and *O-E* is the voltage. The former angle Φ, which was an angle of lag, now becomes Φ′, an angle of lead.

This, of course, is equivalent to a negative reactance. And as it is in series with the rotor winding of the industrial motor *B*, it neutralizes the reactance of the motor's winding which formerly caused the primary current to lag in phase. It therefore produces precisely the same effect as a condenser and improves the power factor.

The stationary frame of the phase advancer which surrounds the direct-current armature winding is really superfluous. The machine may consist of nothing but a drum armature and a commutator. In this case, however, the winding, instead of being placed on the surface of the drum with open slots, would be embedded in holes below the surface, so that the conductors are entirely surrounded by iron. This provides an external path or the flux around the winding.

The low-frequency alternating currents supplied by the slip rings of the main motor induce a magnetic field which slowly revolves in space, while the rapidly revolving armature conductors cut across this field and generate the required leading e.m.f. The field flux of the phase advancer can be readily maintained at precisely the required low frequency due to the slip of the rotor on account of the fact that the phase advancer has no definite poles and runs at no definite speed. The point is that the field of the phase advancer is an induced field and the current which induced it is at the slip frequency of the rotor of the induction motor, and therefore the field flux must be at that same slip frequency.

The phase advancer therefore becomes, in effect, a phase booster, the e.m.f. of which accelerates the current in the rotor structure of the main motor.

Phase advancers are usually constructed, however, with an external stationary frame. This permits the use of open slots on the drum armature and insures more satisfactory commutation.

While phase advancers for large machines are usually driven by small direct-connected induction motors, it is entirely possible to belt them direct to a pulley on the main machine. It is entirely practical to apply the phase advancer to any induction motor now in service, provided it has a wound rotor and slip rings. The power factor may be corrected to 100%, with a variation of from 25 to 150% load.

If a new induction motor is to be designed to be operated with a phase advancer, it can be made considerably smaller than without. Because of the less material involved, the power factor would be lower. When the phase advancer is used this defect is promptly corrected. In fact, the saving in first cost of the large motor would pay a large part of the cost of the phase advancer. If a machine with a high power factor is desired, it is cheaper to build one in which there is a large amount of iron and a small amount of copper and employ a phase advancer than it would be to build a machine in which there was a small amount of iron and an excess of copper without a phase advancer. A 100% power factor cannot be obtained in an induction motor unless a phase advancer or equivalent device is employed.

The losses in a small motor and phase advancer would generally be low; therefore the power required to drive a small motor and phase advancer would be less than that required to drive a large machine of the same rated capacity without a phase advancer. The phase advancer can be applied to an induction motor of any size.

Another feature of this device is the compensation for the reactance in an induction motor as it affects the maximum output. By bringing the current and e.m.f. into phase, the capacity of the machine is considerably increased. In fact, if a phase advancer is applied to an old machine, the horse-power output can readily be increased 25% and the power factor improved besides.

In the design of induction motors a respectable power factor can only be secured by making the clearance between the stator and rotor exceedingly small. When a phase advancer is employed, however, the inherent power factor of the motor does not have to be considered, and the clearance can be considerably increased.

The phase advancer is designed especially for induction motors which run in one direction and operate continuously. If the machine is to be started and stopped frequently, or operated at variable speed, or reversed, it is not practical to use a phase advancer. Its greatest field of usefulness is for large, slow-speed induction motors having an inherently poor power factor, and especially where such machines run all the time and at partial loads. In many large cities the feeders are so heavily loaded that no additional power can be transmitted. If a phase ad-

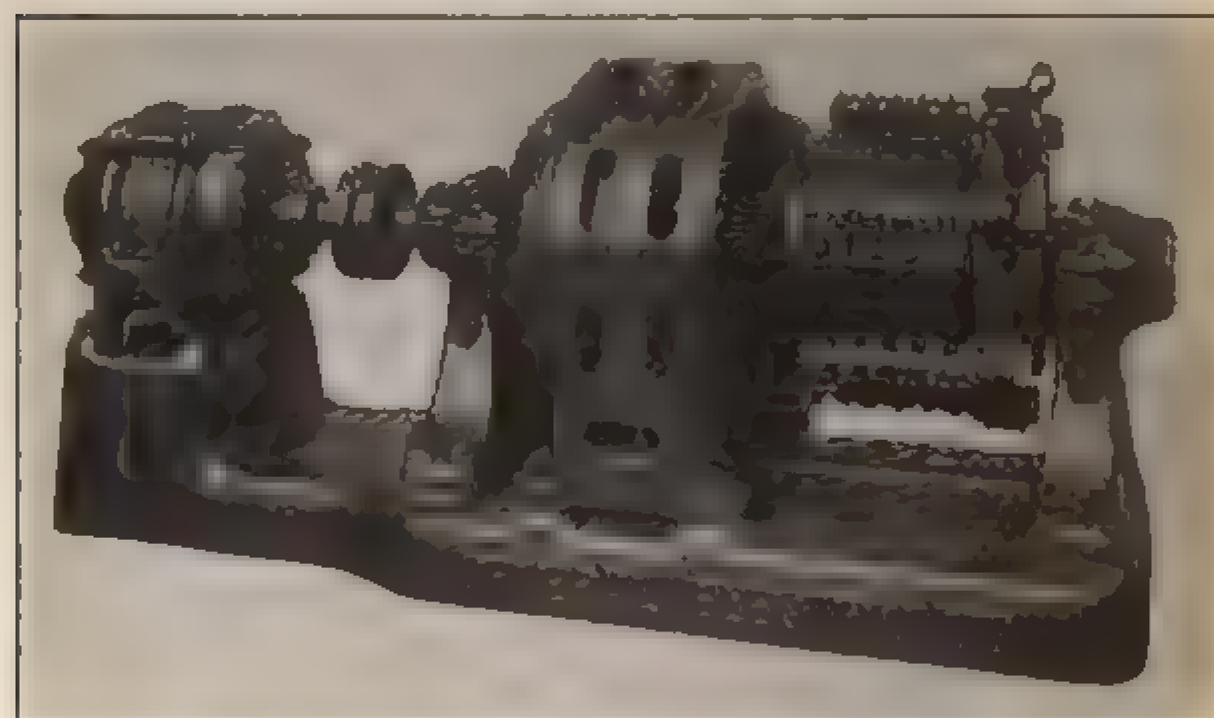


FIG 897 —General Electric phase advancer for 600 K.W. induction motor with type K. T. driving motor.

vancer is introduced on a few large induction motors, the condition is appreciably relieved.

The general appearance of a phase advancer designed by the General Electric Company is shown in Fig. 897.

As an illustration, a 30-K.V.A. phase advancer is capable of changing the power factor of a 1,300-K V.A. motor from 88% lagging to 95% leading. That is equivalent to saying that the motor, instead of requiring a lagging wattless current amounting to 600 K.V.A., will actually relieve the generating system of a wattless load of 400 K.V.A., making a total change in the wattless load of 1,000 K.V.A. to the good.

SECTION XVI CHAPTER VIII

SPECIAL A. C. GENERATORS

INDUCTION GENERATORS

1. Explain the construction and principle of operation of an "induction generator."
2. Upon what does the output of an induction generator depend? What will be the effect upon the output if the line voltage is changed?
3. What determines the voltage and frequency of the delivered power of an induction generator? What will be the effect if the speed of that machine is changed?
4. (*a*) What kind of a machine is required to excite an induction generator?
   (*b*) How is the voltage regulation effected?
5. For what kind of service would an induction generator be used and what advantages are gained from its use?
6. (*a*) Explain the construction and purpose of a "phase advancer."
   (*b*) What is the principle upon which it operates?
7. What is the effect upon the power factor and output of an induction motor designed for operation without a phase advancer if a phase advancer is employed?
8. What is the effect upon the size and cost of an induction motor designed for operation with a phase advancer compared with one designed for operation without?

SECTION XVII CHAPTER I

SYNCHRONOUS CONVERTERS

PRINCIPLES

It frequently happens that the nature of the current received from a source of supply is not suitable for the work to be done. All devices for changing A. C. to D. C. or D. C. to A. C., with or without an accompanying change in voltage, are termed current reorganizers.

The earliest device of this kind was a **revolving commutator.** Consider a two-pole synchronous motor running 3,600 r.p.m. on a 60-cycle circuit. In addition to the circuits required for its operation, let there be two slip rings connected to two half-segments of metal insulated from each other. If alternating current is delivered to the slip rings, a rectified direct current will be obtained from the brushes on the segments, for the connections between the slip rings and the brushes on the segments reverse with each alternation. Such commutators have the advantage of implicity, efficiency and cheapness. They are possible in small sizes only, however, for sparking becomes a certainty if any considerable amount of energy is to be handled. The direct current is disjointed and far from continuous. The voltage is fixed by that on the A. C. side. While some of these devices are still in use for changing A. C. to D. C. for operating arc lamps in connection with moving picture projecters, the majority of such commutators have been abandoned because of their unsatisfactory operation.

The most natural way to get direct from alternating current is to use a **motor-generator.** Two machines, one an alternating-current motor and the other a direct-current generator, can be belted together even though the voltages and speeds differ widely. A better method is to have the machines designed for the same speed and mounted on the same bed plate with their shafts directly connected. Depending on the size, such outfits will have an efficiency ranging from 65 to 90%.

For certain classes of work there is an advantage in the machine known as a **dynamotor.** This consists of a single field structure carrying one winding, within which there revolves an

armature carrying two windings. One of these windings terminates in a commutator and the other in a pair of slip rings. Any ratio of transformation desired may be had in the original design, but once this ratio is established it cannot be altered. The field winding is excited from the D. C. brushes. The machine is chiefly used for transforming 110 volts D. C. to 75 volts, 15 cycle, A. C., for the purpose of ringing telephone bells from central exchanges. An interesting feature of this machine is that there is very little field distortion. As one winding acts as a generator and the other as a motor, the tendency for the armature reaction on the one is approximately balanced by that of the other and the field is practically undis-

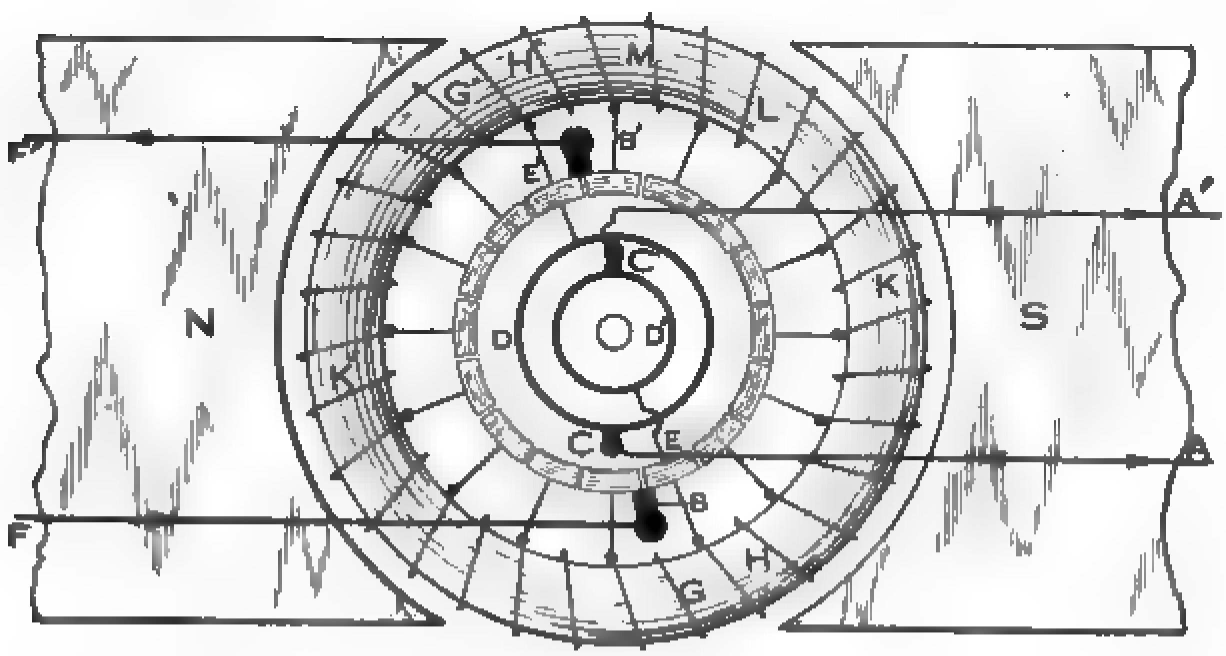


FIG. 898.—Principle of rotary converter.

torted. The brushes may therefore rest on the theoretical neutral at all times. This machine is cheaper to begin with and more efficient in operation than a motor-generator set.

The most widely used device for changing A. C. to D. C. is the rotary or **synchronous converter.** This machine is so named to distinguish it from the static or stationary transformer which has no moving parts. The dynamotor resembles a static transformer in its armature in that it contains two windings on the same core. The synchronous converter resembles the autotransformer in this particular as it contains but one winding which is common alike to both sides of the system.

The rotary converter is primarily a D C. generator, fitted with slip rings. If it was a single-phase machine with a bipolar

field, its construction would be as shown in Fig. 898. A ring armature winding is here shown for simplicity, but in practice the winding is always of the drum type. This winding terminates at the commutator on which rest the brushes *B-B'*. On an extension of the commutator and insulated therefrom, or elsewhere on the shaft wherever convenient, are placed two slip rings *D-D'*. One of these is tapped to a commutator segment *E'* and the other to a segment *E*. Upon these slip rings rest the brushes *C-C'*. The field winding, not shown, is connected in shunt with the D. C. brushes *B-B'*. If alternating current is supplied through the lines *A-A'*, it will flow via the circuit *A-C-D-E'-B'-F'* and thence through the direct-current circuit back to *F-B-D'-C'-A'*. At this particular instant, and twice in each revolution of the armature, the A. C. circuit is metallically connected with the D. C. circuit

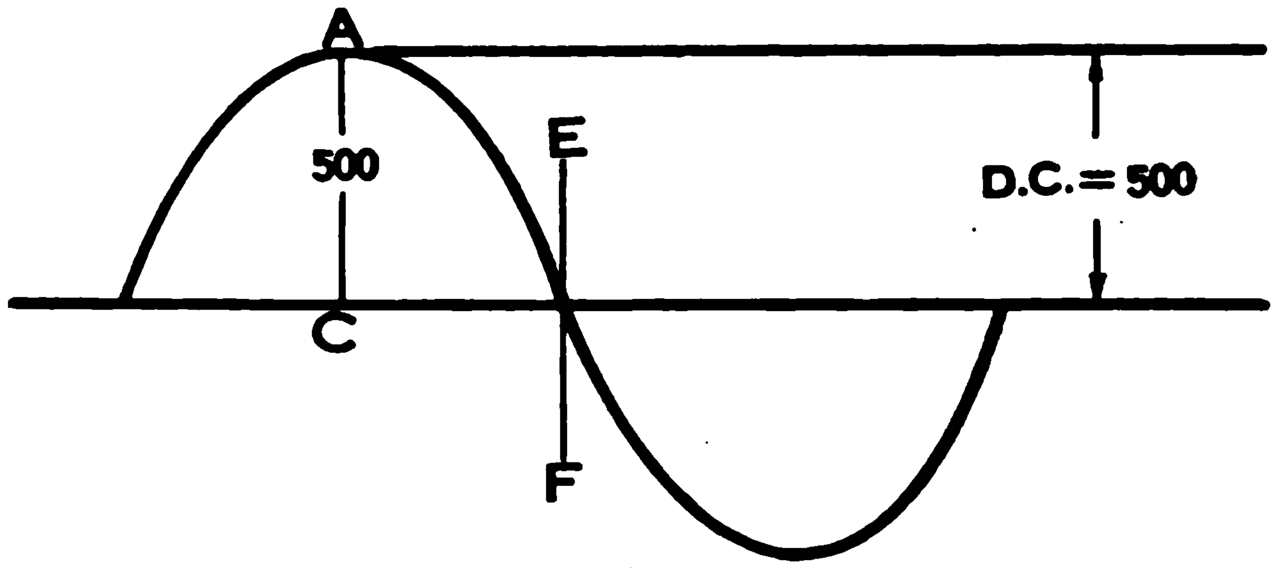


FIG. 899.

through slip rings and segments without any of the armature winding intervening. The difference of potential on the D. C. side between the lines *F-F'* will therefore be equal to the maximum height of the A. C. wave impressed upon *A-A'*. This point on the curve shown in Fig. 899 is *A-C*, and this voltage is impressed on the D. C. side. If the maximum height of the A. C. wave is 500 volts, then 500 volts will be measured on a D. C. voltmeter across *F-F'*, but an A. C. voltmeter across *A-A'* indicates only the virtual voltage which, in a single-phase system, would be 0.707 of the maximum height of the A. C. wave, in this case approximately 350 volts. This ratio between the A. C. and D. C. voltages is practically fixed within very narrow limits. Thus, while in a motor-generator the voltage ratio may be different and variable at will, in a dynamotor the voltages on the two sides may be different, but, once having been fixed, they cannot be altered; in the synchronous converter they are fixed to begin with.

At the same time that the current flows from the A. C. circuit to the D. C. by the path mentioned, another current will flow through the armature winding from *A-A'* via the following circuit: *A-C-D-E'-G'-K'-G-E-C'-A'* and *A-C-E'-H'-K-H-E-C'-A'*. At this instant the armature acts as a motor and rotates under the impulse of the current thus received. A quarter of a revolution later the segment *E'*, with its tap to the ring *D*, will have moved to the point *K*, and the segment *E*, with its tapping point to the ring *D'*, will have moved to the point *K'*. At that instant the e.m.f. wave has fallen to zero as pictured at *E-F*, Fig. 899. The alternating-current wave now being zero, the delivered e.m.f. from the brushes *B-B'* must be wholly due to generator action, and the machine becomes a generator running by the momentum which it acquired from its boost as a motor, a quarter of a revolution earlier. Therefore in a single-phase bipolar machine the armature reverses its functions from motor to generator every quarter of a revolution. At all intermediate points other than those just referred to, the armature is partly a motor and partly a generator at the same time. Thus in Fig. 900 consider that the coil *G'* has rotated half-way to the position *K*. At that point the A. C. wave may be supposed to have fallen to the point shown by the line *F-G*. As the secondary e.m.f. must be maintained at the maximum value of the A. C. wave, the coils on the armature must generate the difference between what the A. C. source furnishes and what the D. C. line requires. Thus if the A. C. source supplied the voltage *G-F*, the armature winding must supply the balance *F-E*. The current from the A. C. source converts part of the armature winding from the tapping point upward into a generator, while the portion from the tapping point downward acts as a motor. The actions in the various coils differ, depending on their relative positions with respect to their tapping points between slip rings and commutator segments. The actual currents in these windings differ widely.

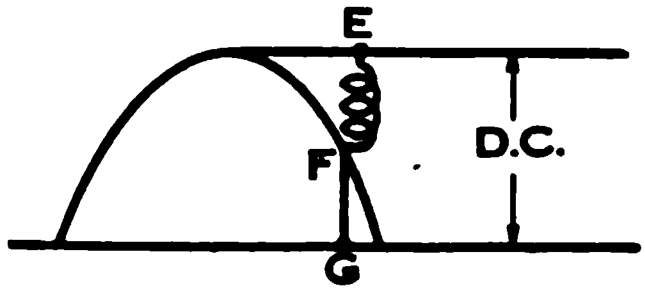


FIG. 900.

The conditions may be shown more clearly in Fig. 901. Let *A* represent the armature of the rotary and *E-F* and *B-G* the two paths through it. In the position shown in Fig. 898, where

the tapping points from the rings under the A. C. brushes are in contact directly with the segments under the D. C. brushes, the current from the A. C. source will flow from L, Fig. 901 directly to M, on the D. C. side and thence through the load and back

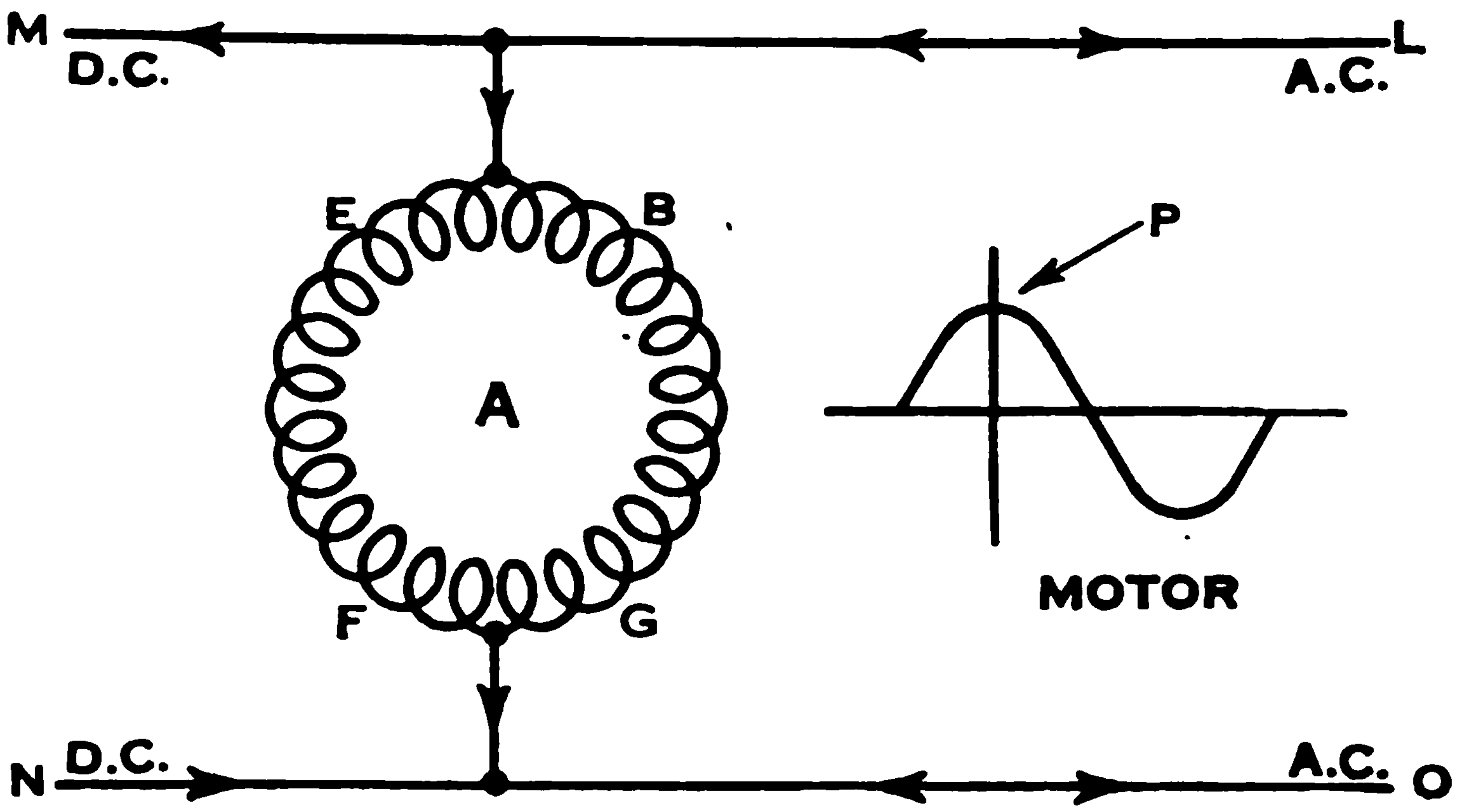


Fig. 901.

from N to the A. C. side, O. At the same time the two parallel paths through the armature carries current through E–F and B–G in multiple from L. of the A. C. source to O, and the machine oper-

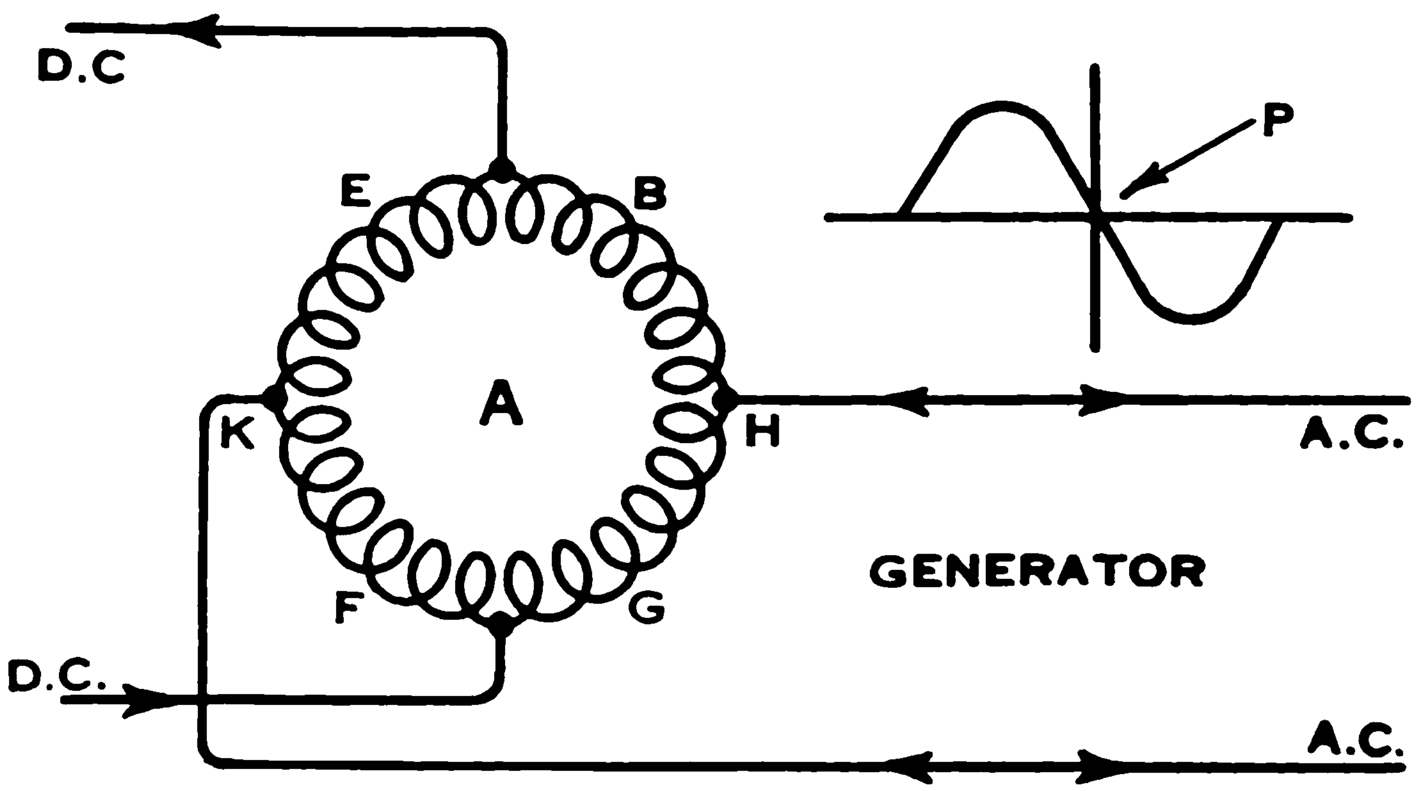


Fig. 902.

ates as a motor. This condition exists when the A. C. wave is at its crest, indicated at the point P. If now the armature in Fig. 898 be rotated until the coil H' reaches the point K, and the coil G reaches K', the conditions will be as shown in Fig. 902. Here

the A. C. wave has reached zero, as is shown at P in Fig. 902. The action is now wholly that of a generator, and there being no difference of potential between the A. C. lines at this instant, a current flows through the two parallel armature paths F-E and G-B to the direct-current circuit and return. For an inter-

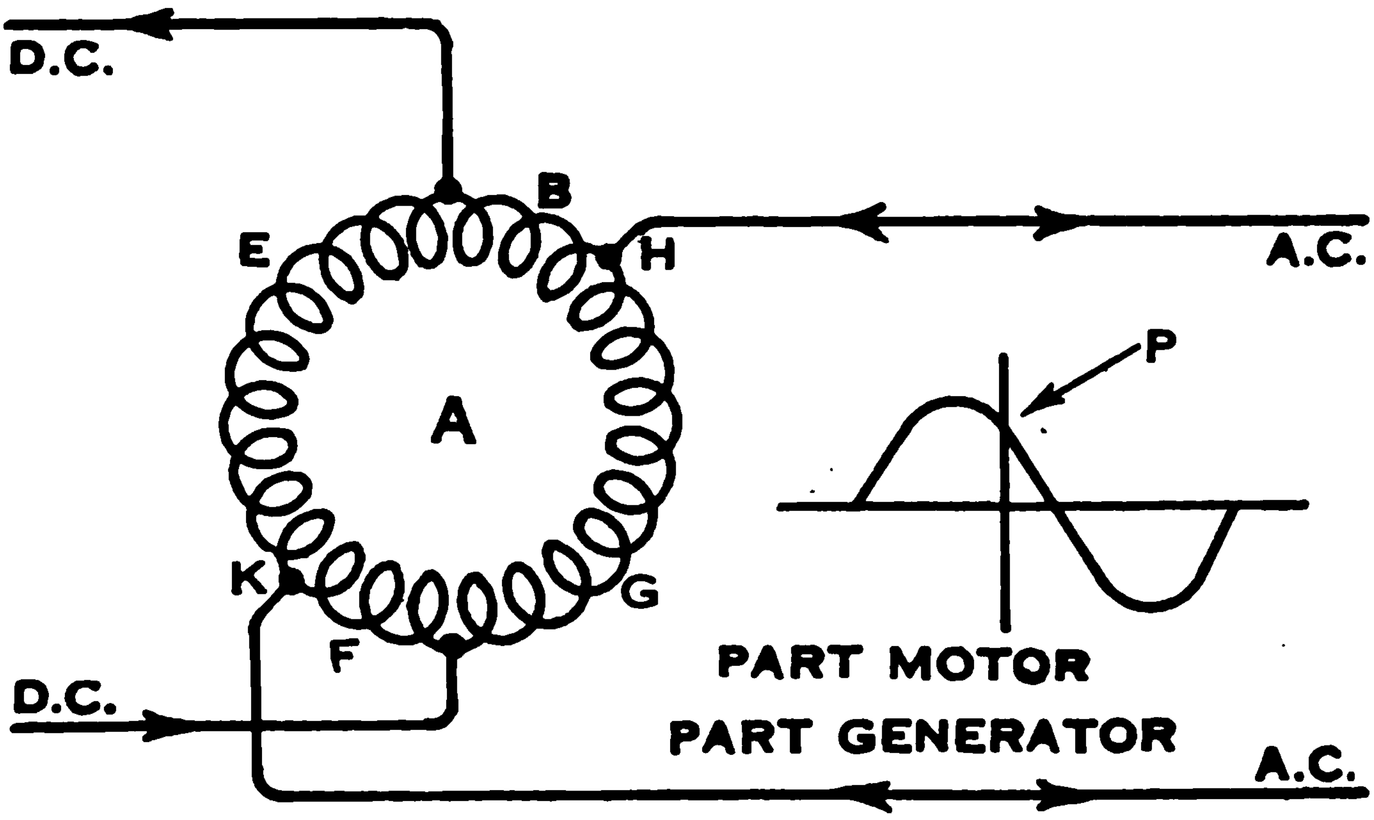


Fig. 903.

mediate position of the armature, the relation of the tapping point for the A. C. brushes with respect to the D. C. brushes may be pictured by Fig. 903. The point on the A. C. wave is again shown on the curve at P, midway between the crest and the zero point. Part of the winding, B-H, now becomes a generator, supplying to the D. C. circuit what the A. C. wave lacks, the re-

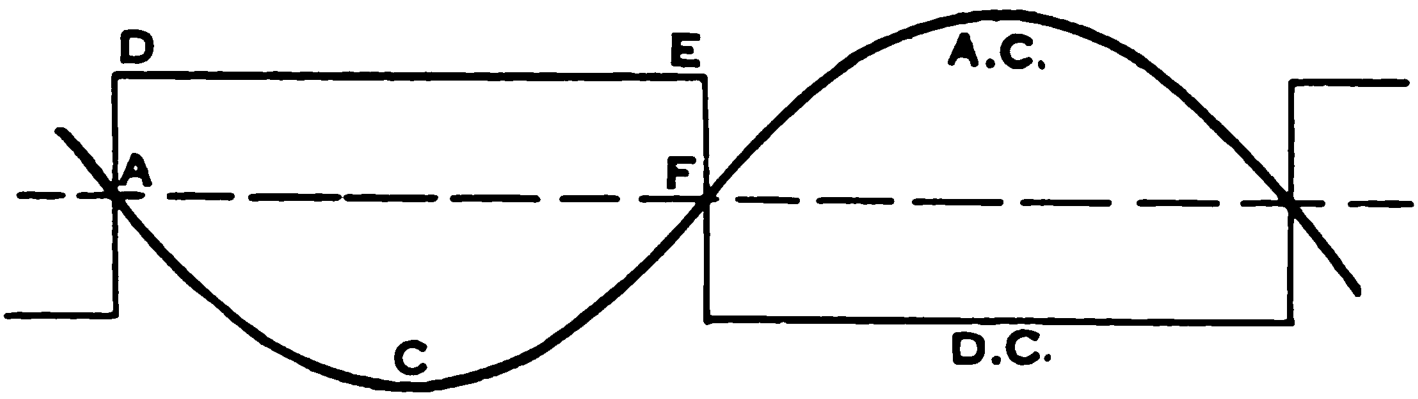


Fig. 904.

maining, G-H, acting as a motor. Likewise the portion F-K becomes a generator and the portion, K-E, a motor. The change from the generator action in Fig. 902 to the motor action in Fig. 901 is accomplished gradually and continuously.

The actual current that flows in the various coils of a rotary armature differ from each other at any instant, depending on

their distance from the tapping point of the A. C. rings. Thus take the current in the coil, K, Fig. 898, which is midway between the two tapping points for the slip rings. The direct current in this coil is of continuous value throughout a half revolution and only reverses when said coil passes under the direct-current brush. Let this current be represented by the line A-D-E-F, Fig. 904. The alternating current in this portion of the arma-

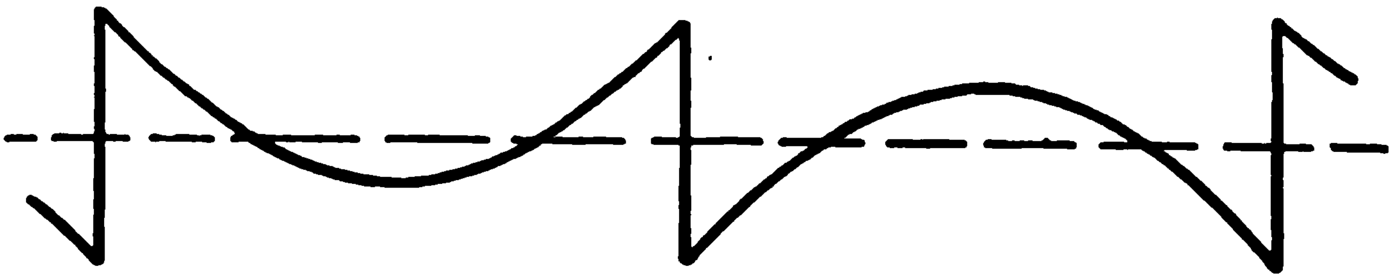


FIG. 905.

ture, which includes the coil K, will be a maximum when the armature is in the position shown and will become zero when the coil K passes under the brush B—that is, the alternating current in the coil K will reverse at the same instant as the direct current. As the alternating current is that due to motor action and the direct current due to generator action, these two are in the opposite directions, hence the alternating current in this coil may be represented by the curve A-C-F. The current which would really circulate in the coil will be the net difference between these

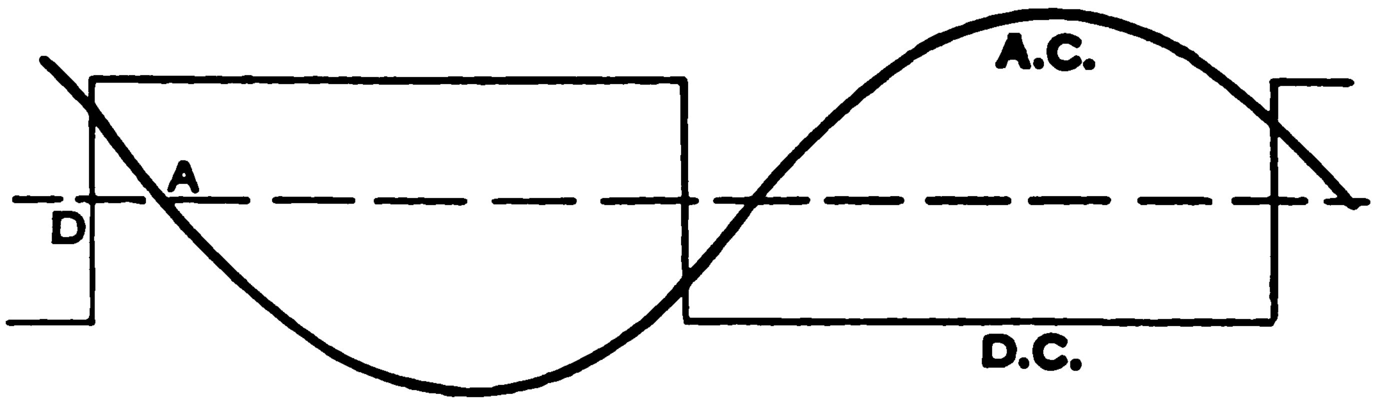


FIG. 906.

two and may be computed by adding the ordinates representing the two separate currents. The result of so combining the currents will give the curve shown in Fig. 905. It will be noticed that the average of these two currents is much less than that represented by the direct-current wave alone, hence the heating effect, which is proportional to the square of the current, will be less for that particular coil than if the machine were acting as a generator. The coils on either side of K closer to the tapping points will not have their direct currents pass through zero at

the same time as the alternating current. Thus another coil such as the one at *L*, reversing its direct current at a different time from the reversing of the D. C., would have its zero point pictured at *A*, Fig. 906, while the direct current would reverse at

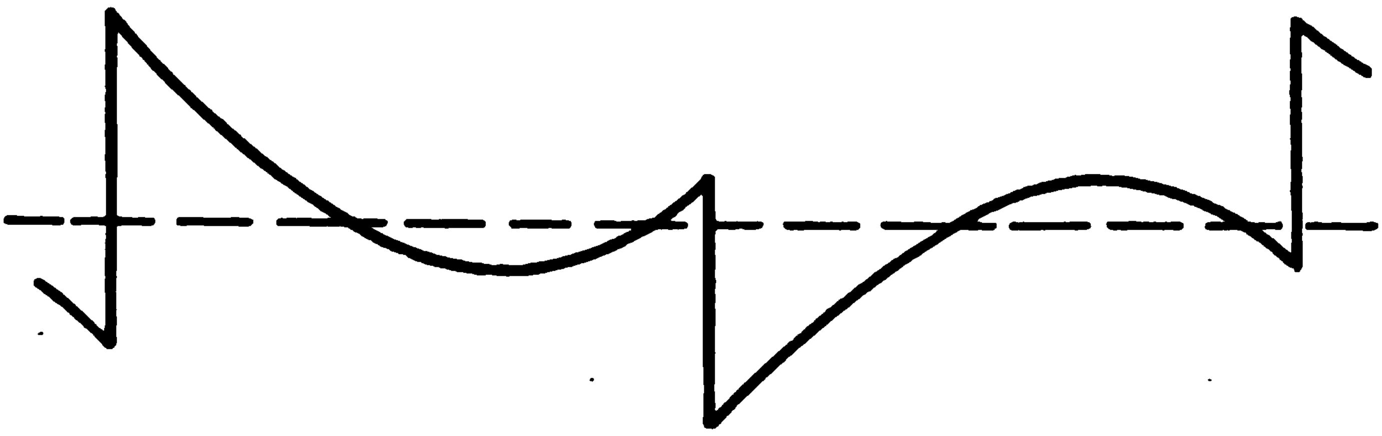


FIG. 907.

D. Combining these two values gives a resultant current in Fig. 907. As the tapping-in point is approached the average current in each coil becomes greater. Thus a coil still nearer such a point, as at *M*, Fig. 898, would have a direct current in it

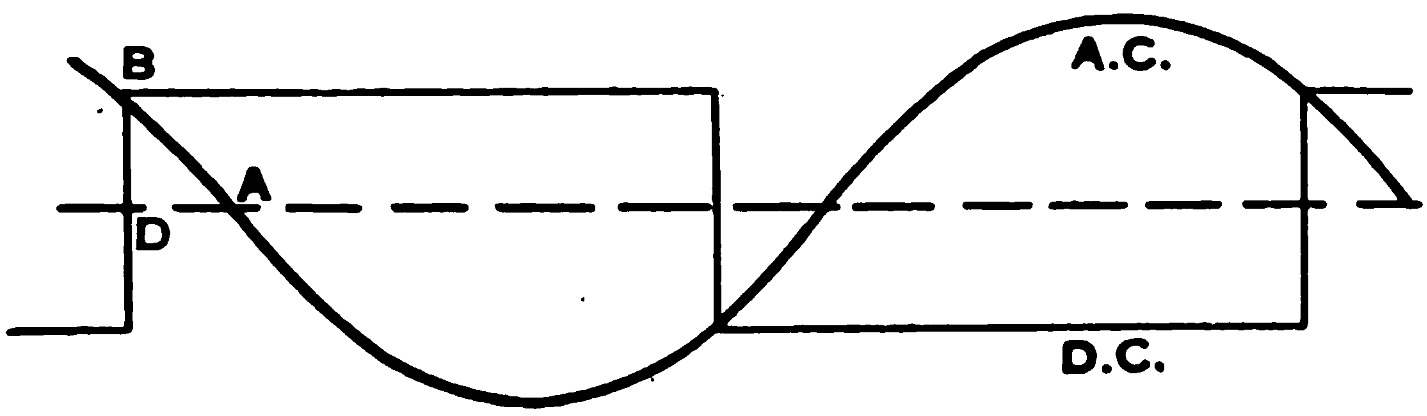


FIG. 908.

which would reverse at the point *B*, Fig. 908, of the same value as the alternating current *D-B*. Adding these ordinates gives the line *C-F*, Fig. 909, and shows to what an extent the current may rise when A. C. and D. C. values are in the same direction

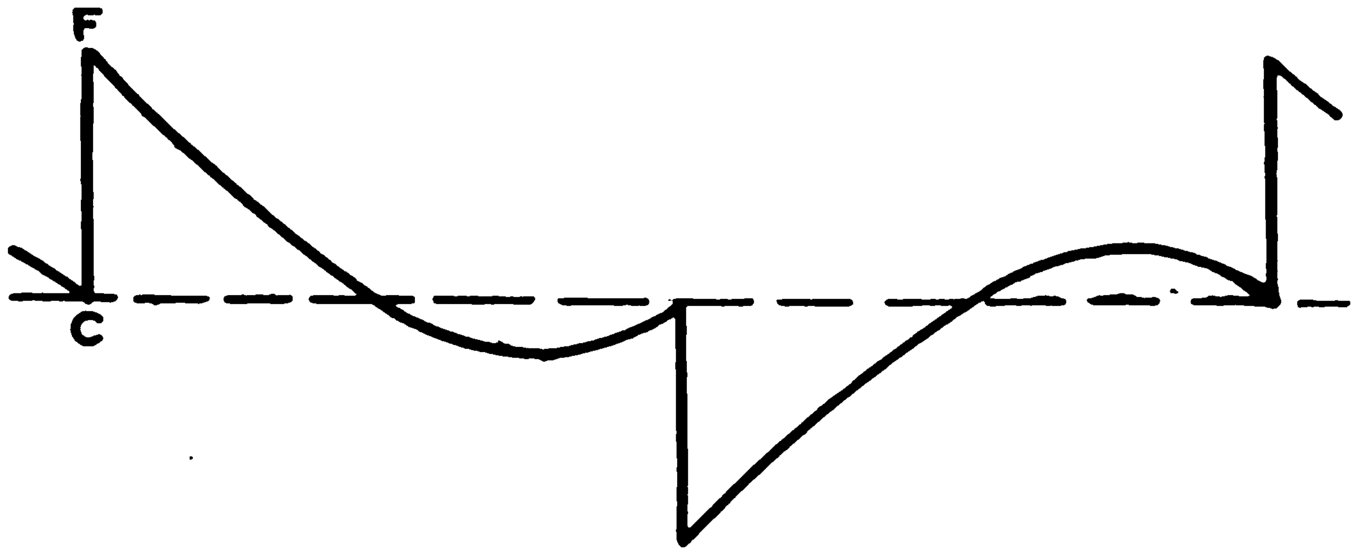


FIG. 909.

The resultant current in each of the coils is therefore different, and a different heating effect is produced, the coils near the tapping point heating considerably more than the coils in the vicinity of K. However, as the number of phases and the number of tapping points increase, the heating effect becomes more uniform and the current passes more directly from the A. C. source to the D. C. circuit without being obliged to pass so far through the armature winding. The average heating effect therefore falls, and the capacity of the machine as a rotary compared with its capacity as a D. C. generator increases. In a single-phase rotary the sum of the heating effects in the armature winding is greater than the heating produced in the same machine operating as a generator, because the maximum value that the combined currents reach in the coils near the tapping-in points is very much higher than the direct-current generator's current alone.

SECTION XVII CHAPTER I

SYNCHRONOUS CONVERTERS

PRINCIPLES

1. Explain the principle of the rectifying commutator for changing A. C. to D. C. Is it reversible? What are its advantages and disadvantages?

2. Explain the advantages and disadvantages of a motor-generator set for changing A. C. to D. C. Is it reversible?

3. Explain the construction of a "dynamotor." What are its advantages and disadvantages? How great is its armature reaction?

4. Explain the principle of the "rotary" or "synchronous" converter. How is it constructed? Sketch.

5. What are the e.m.f. and current ratios between the A. C. and D. C. sides of a single-phase converter?

6. Explain under what conditions the synchronous converter operates:

(*a*) Wholly as a motor.

(*b*) Wholly as a generator.

(*c*) Partly as a motor and partly as a generator.

(*d*) Sketch three A. C. e.m..f waves, and mark on each the point represented in one of the three above conditions.

SYNCHRONOUS CONVERTERS

CONNECTIONS

The kilowatt capacity of machines when operated as direct-current generators and rotary converters respectively is given in the following table:

Kilowatt Capacity Ratios

Continuous D. C. generator	100%
Single-phase rotary	85%
Two-phase rotary	164%
Three-phase rotary	134%
Six-phase rotary	196%

Here it will be observed that a machine having an output of 100 kilowatts as a D. C. generator would only transform 85 kilowatts as a rotary converter. If, however, the machine were connected up as a two-phase rotary, its capacity would be increased to 164 kilowatts. A three-phase rotary has a somewhat smaller capacity because there are only three tapping points to the armature, while in a two-phase there are four. The greatest capacity of all is obtained in a machine connected as a six-phase rotary. Such a machine will transform 196 kilowatts as compared to its direct-current rating of 100 kilowatts as a generator.

Early rotaries were designed for 25 cycles. In later years it was possible, by improved design, to build large rotaries for 60 cycles. The difficulties which prevented them being so operated before were troublesome commutation and high speed. A rotary must necessarily be multipolar in construction, in order to operate on a given frequency at a permissible speed. This is particularly true if the machine is of large size. Otherwise the peripheral velocity will be too great. In large sizes the spacing between points of opposite polarity on the commutator is not sufficiently great unless the commutator is made of large diameter. With great diameters, high commutator velocity results. At the present time a commutator velocity of 5,000 feet per minute is possible and a spacing of about 7½ inches between brushes of opposite potential. This represents about the maxi-

mum safe commutator velocity and the minimum spacing between brushes that is considered practical.

Single-phase rotaries are seldom, if ever, designed save for welding and a few other special operations. Rotaries are two phase, three phase and six phase. If capacity alone is to be considered, the six-phase rotary has a decided advantage over the three-phase and two-phase machines, and the winding is in no way different from any other machine. The only difference in construction is in the number of slip rings and the tapping points from these rings into the winding. Three-phase rotaries employ three slip rings; two-phase, four rings; and six-phase, six rings.

Transformer Connections to Rotaries

Fig. 910 shows the connections between two single-phase transformers supplied with two-phase currents and the connections of the low-tension windings to a rotary armature. For convenience, the armature is pictured as a circular Gramme ring winding, and it is assumed that it is placed in a bipolar field. The transformer terminals 1-1, for the first phase, connect to brushes which are placed upon slip rings which tap points 1′-1′ diametrically opposite to each other in the armature winding. Terminals 2-2, of the second phase, lead to brushes 2′-2′ which in turn rest upon slip rings which tap two diametrically opposite points in the armature winding, these two latter points being 90° away from the first two points. Should the rotary have four poles instead of two, each of these rings would tap at one additional point, and the number of tapping points for each ring would increase directly with the number of pairs of poles in the rotary.

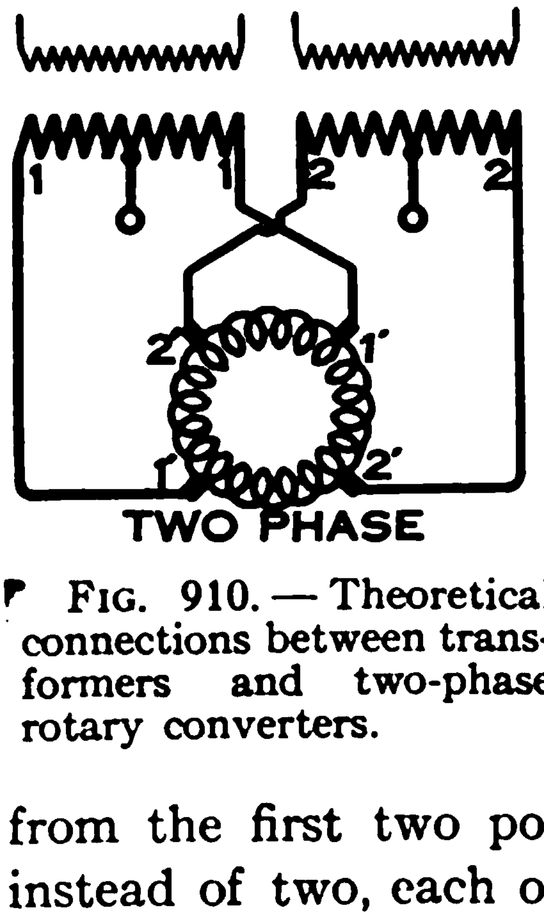


FIG. 910.—Theoretical connections between transformers and two-phase rotary converters.

Fig. 911 represents three single-phase transformers with the low tensions connected in Δ, these terminals leading to three points 120° apart in the armature winding. Fig. 912 shows the same arrangement save that the transformer secondaries are in Y instead of in Δ.

A six-phase rotary is shown in Fig. 913. This machine differs in no way from a three-phase machine save that it has

six rings tapped into the armature winding 60 electrical degrees apart instead of 120. The three secondaries of three transformers, supplied with three phase on their high-tension wind-

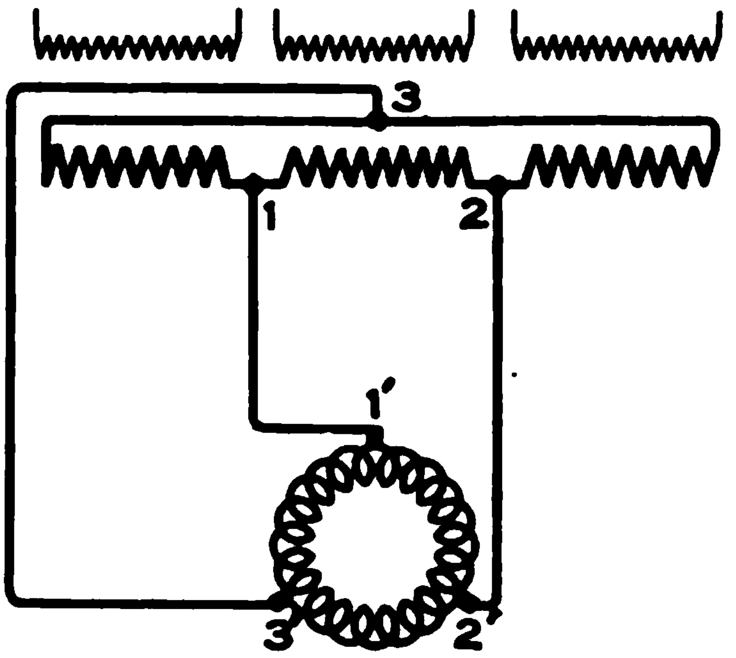


FIG. 911.—Theoretical connections between Δ-connected transformers and three-phase rotary converter.

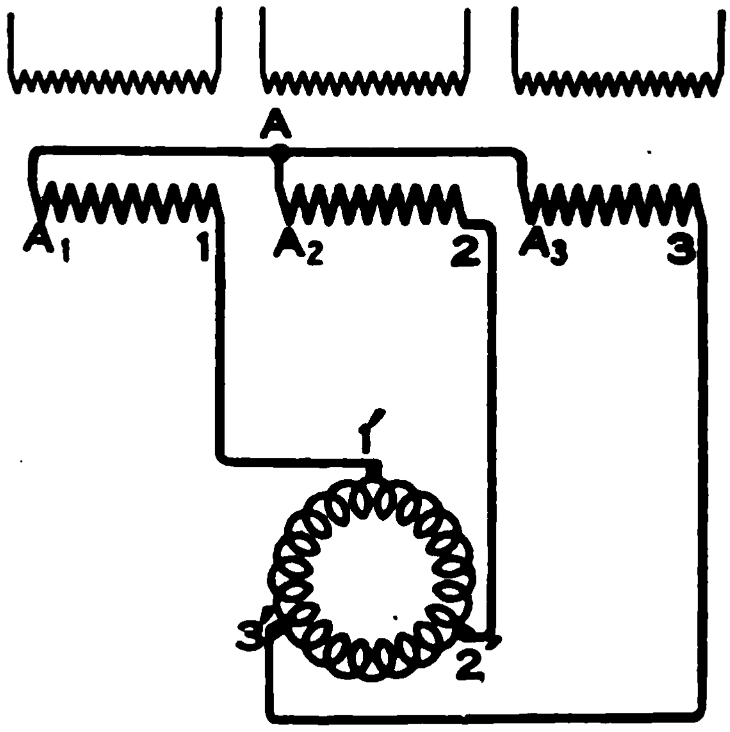


FIG. 912.—Theoretical connections between Y-connected transformers and three-phase rotary converter.

ings, are connected separately to the brushes on the slip rings; thus phase one has its terminals 1-1′ led to the brushes 1-1′ on the rotary which are 180 electrical degrees apart. Hence the term **diametrical connection.** Phase two connects to two of the

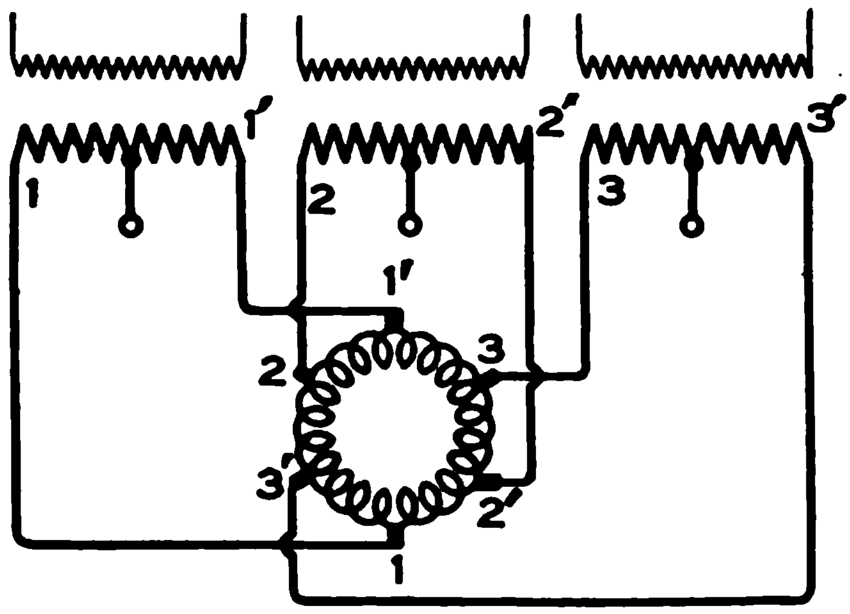


FIG. 913.—Theoretical connections between transformers and diametrically connected six-phase rotary converter.

points diametrically opposite each other but 60° away from the first set, while phase three likewise connects to two diametrically opposite points each of which is 60° removed from each of the preceding tapping points. This is a widely used connection.

A six-phase Y connection is shown in Fig. 914. This differs from Fig. 912 in that each of the three transformers is provided with two secondary windings. The two sets of secondaries are independently connected up in Y. The terminals of the first set are connected to points 1, 2 and 3, 120° apart, and the terminals of the second set are connected to the points 1′, 2′ and 3′, also 120° apart and each removed 60° from the preceding set. In both of these connections, three-phase currents, 120° apart in the transformer, are split in the rotary into six-phase currents 60° apart in phase. Further, the two sets of secondary windings

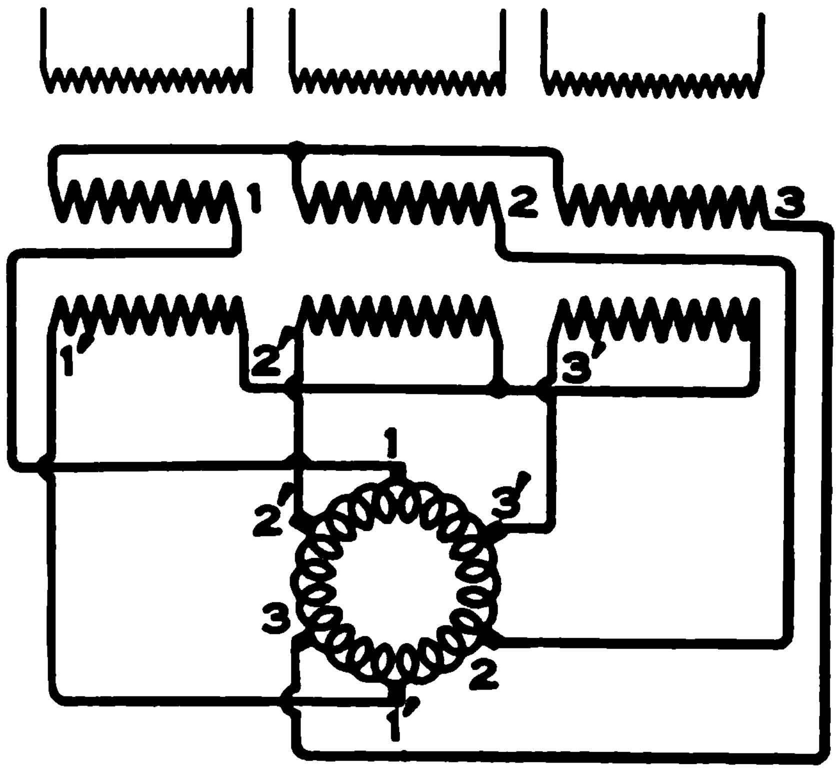


FIG. 914.—Theoretical connections between transformers with duplicate secondaries and six-phase diametrical rotary converter.

in Fig. 914 may be connected in Δ for six-phase operation as well as in Y.

Voltage Ratios of Rotaries

The potential ratios of rotary converters are practically fixed. They are subject to slight variations, however, depending upon, first, the kind of A. C. employed—that is, whether it be two, three or six phase; second, upon the shape of the e.m.f. wave, whether it be flat top or peaked; third, on the construction of the rotary, particularly upon the percentage of armature circumference embraced by the pole pieces; fourth, the resistance of the armature winding on the rotary; fifth, the operating conditions such as brush position, the method of excitation and whether the rotary is used to convert A. C. to D. C. or D. C. to A. C.

The no-load voltage ratio of a rotary converter may be expressed as follows. The maximum A. C. voltage has the same ratio to the D. C. voltage as the length of the chord which subtends the arc made by the adjacent A. C. taps bears to the diameter of the circle. To illustrate, in a single-phase machine the A. C. taps are 180° apart and therefore the chord of that arc is equal to the diameter and the maximum A. C. and D. C. voltages are the same. If the rotary be three phase the connections of the A. C. taps on the windings are 120° apart. The length of the chord is 0.866 of the diameter, and the maximum A. C. voltage is 0.866 of the D. C. voltage. Suppose in the six-phase diametrical the taps are 180° apart on the A. C. side, then the relations are the same as on single phase, while in six-phase Δ the connections are 120° apart as in three phase and the relations the same as in that case. In all cases the A. C. voltmeter reads less than the maximum, and the amount will depend upon the shape of the A. C. wave. With a sine wave, it will be 0.707 of the maximum.

The following table gives the no-load ratios for voltages of rotaries compared to the voltage of the same machine as a D. C. generator.

Continuous, D. C.	100%
Single phase, A. C.	71.5%
Two phase, A. C.	71.5%
Three phase, Y or Δ	61%
Six phase Y or Δ	61%
Six phase "diametrical"	71.5%

It will be observed that the 70.7% theoretical is increased to 71.5%. This is due to the shape of e.m.f. wave and percentage of armature circumference embraced by poles.

The full-load ratios differ somewhat, and the following table shows the extent to which the A. C. voltages must be increased in order to deliver the correct D. C. voltage.

Continuous, D. C		100.0%
Two phase and six phase	550 E	72.5%
	250 E	73.0%
	125 E	73.5%
Three phase and six phase Y or Δ	550 E	62.0%
	250 E	62.5%
	125 E	63.0%

It will further be noted that the A. C. voltage has to be increased in proportion as the D. C. voltage is lowered. This is because the losses in low-voltage rotaries are higher in proportion than in high-voltage rotaries.

Current Ratios of Rotaries

The current ratios will in general be the inverse of the voltage ratios. The following table illustrates this.

Continuous, D. C.	100.0%
Single phase	141.0%
Two phase	70.7%
Three phase	94.3%
Six phase	47.2%

Here the single-phase current input must be practically double or 141% of the single-phase voltage, which would theoretically be 70.7%.

The three-phase current input in each wire is nearly equal to the direct-current output. The six-phase machine receives in each of the six wires at 100% power factor approximately one-half of the current on the D. C. side.

SECTION XVII CHAPTER II

SYNCHRONOUS CONVERTERS

CONNECTIONS

1. What are the relative k.w. capacities of various synchronous converters compared to the capacity as a direct current generator?

2. Why is the capacity of a single-phase converter less than, and the capacity of a polyphase converter more than, the capacity of the same machine as a D. C. generator?

3. Why is the capacity of a six-phase converter greater than that of a three-phase converter?

4. Sketch suitable connections between single transformers and a two-phase converter.

5. Sketch suitable connections between single-phase transformers connected in Δ and a three-phase converter.

6. Sketch connections between three single-phase transformers connected in Y and a three-phase converter.

7. Sketch connections between three single-phase transformers connected to a six-phase diametrical converter.

8. What are the relative voltages which must be impressed upon the A. C. side of various converters to give 100 volts on the D. C. side, at no load.

9. What are the various voltages which must be impressed upon the A. C. side of different converters to deliver 100 volts on the D. C. side at full load? Why the difference?

10. What are the relative currents in each wire leading to the A. C. end of different types of converters in order to deliver 100 amperes on the D. C. side?

SYNCHRONOUS CONVERTERS

D. C. VOLTAGE REGULATION

As the ratio of the A. C. to D. C. voltage of a converter is naturally fixed, when a variable D. C. e.m.f. is required the rotary converter as originally designed is not suitable.

There is some slight inherent regulation in a rotary due to the reactance of the armature, which tends to help the D. C. voltage under increase in load, but this is obtained by a sacrifice of the power factor.

There are five principal methods of varying the D. C. e.m.f. of rotary converters.

Phase Control.—The first is by phase control. This consists in inserting an external artificial reactance in series between the low-tension side of the transformer and the A. C. brushes on the slip rings.

The e.m.f. of any machine is proportional to the product of three quantities, flux, conductors, and speed. In a direct-current generator, driven at a constant speed, the e.m.f. will vary with the flux, which in turn is varied by the field excitation. In a rotary converter the speed is constant because the machine is a synchronous motor. The number of conductors is of course constant. The flux cannot be varied by varying the field excitation, as in a direct-current machine, for any alteration of the field excitation results in permitting a current to circulate in the armature in such a direction as to either supplement or oppose this excitation, with the result that the total magnetic flux remains unaltered.

It must be remembered that in an A. C. generator, a lagging current caused a weakening of the field and a leading current tended to strengthen the field. In a synchronous motor, the magnetic reactions are reversed.

If the excitation of a synchronous motor or converter is such that the current and e.m.f. are in phase as in Fig. 915, the current which flows in the armature will oppose the flux during a part of the cycle and aid it during another portion of the cycle, with the result that the average magneto-motive-force of the

armature, with respect to the pole, is zero. Assume that the current circulating in the field produces 60 units of magneto-motive-force and that this causes 60 lines of force to pass through the armature. If now the excitation of the field is weakened to 30 units as in Fig. 916, the current entering the armature will lag with respect to the e.m.f., and this current will circulate

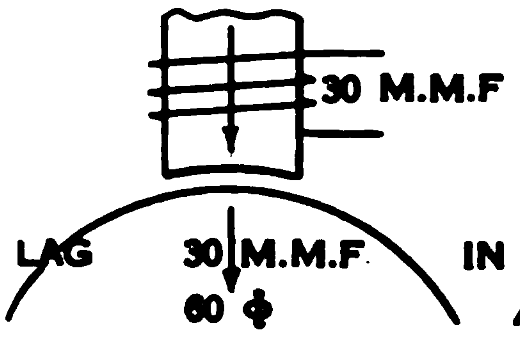


FIG. 916.

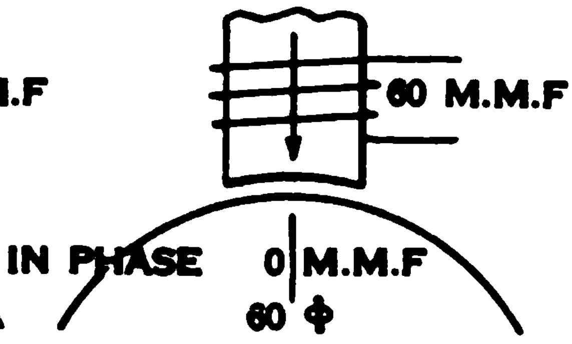


FIG. 915.

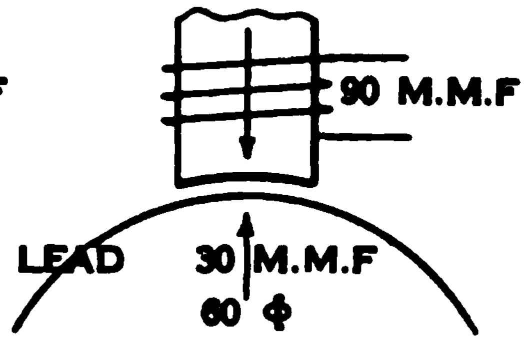


FIG. 917.

With under-excitation, current lags; With over-excitation, current leads.

The flux, due to armature m.m.f. plus field m.m.f. is always constant.

In an Alternator
A lagging current bucks the flux;
A leading current boosts the flux;

In Rotary Converter or Synchronous Motor
A lagging current boosts the flux;
A leading current bucks the flux.

in such a way as to produce 30 units of magneto-motive-force which supplements that of the field, producing a total of 60 as in the first case. This will bring about the same 60 magnetic lines of force as before. If, however, the field excitation is increased to 90 units of magneto-motive-force as in Fig. 917, the current entering the armature will lead with respect to the e.m.f. This current will circulate in such a manner as to develop 30

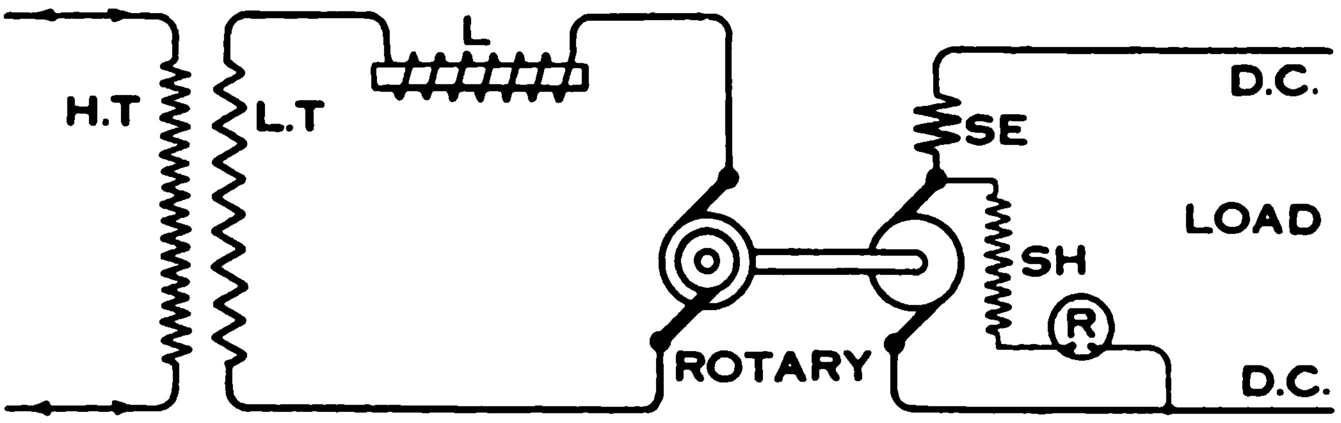


FIG. 918.—Phase control of the D. C. voltage of a rotary converter by reactance in the A. C. circuit cooperating with a compound winding on the D. C. field.

units of magneto-motive-force in opposition to the field. The net difference will, however, still be 60 units and will produce the same 60 magnetic lines of force. Thus the flux due to the geometric sum of the armature's magneto-motive-force and the field's magneto-motive-force is always a constant quantity.

A series winding on a rotary converter provides a means of automatically varying the magneto-motive-force of the field in proportion to the direct-current load.

If an alternating current on its way to a compound rotary converter from the low-tension winding of a transformer, Fig. 918, flows through an inductance L, the voltage which reaches the slip rings will either be diminished or increased, depending on whether the current in this inductance lags or leads with respect to the transformer's e.m.f. As has already been explained, the variation of the excitation of a rotary can be made to bring about this alteration of phase relation of current and e.m.f. If the excitation of the rotary is small, then the incoming current will lag behind the e.m.f. This current will induce, in the coil L, an e.m.f. which is 90° behind the current. Thus in Fig. 919, if A-B is the voltage delivered by the transformer and

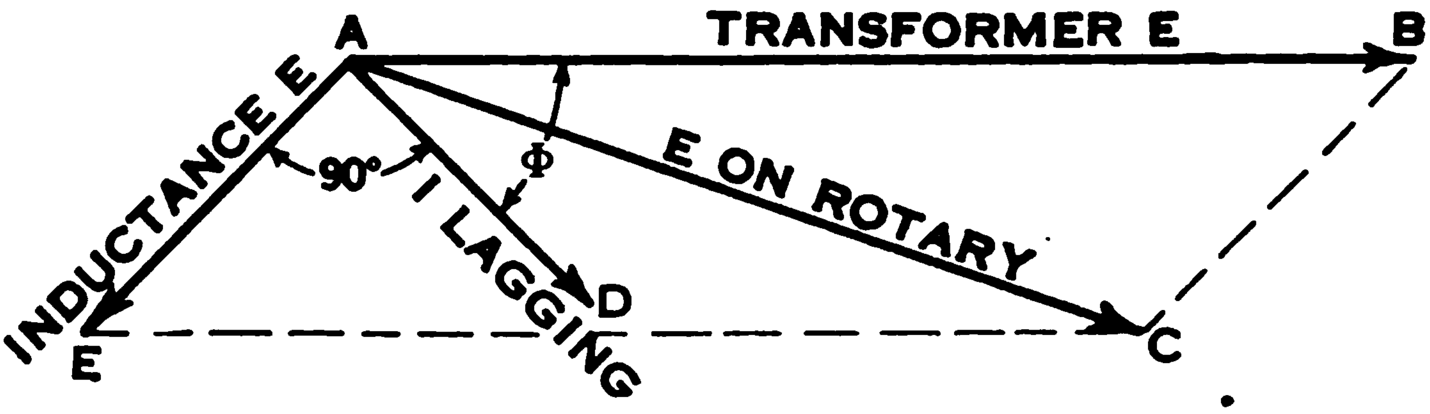


FIG. 919.

A-D is the current lagging Φ° behind it, due to the under-excitation of the rotary, and A-E is the inductive voltage due to L, 90° behind the current, then the voltage which reaches the slip rings will be the vector sum of A-B due to the transformer, and A-E, due to the inductance, or A-C.

If, however, the excitation of the rotary be increased as by the application of a load and its consequent effect upon the series winding, then the condition will be as in Fig. 920. Here the current A-D leads the transformer's voltage, A-B, by the angle Φ. The voltage of the inductance coil L now swings into the position A-E still 90° behind the current, but this voltage is now in the same general direction as that of the transformer A-B instead of opposed to it. The vector sum of A-E and A-B is now A-C. As the increase in excitation of the rotary is brought about gradually in direct proportion to the load, the length of the line A-C will be the voltage on the A. C. slip rings which also rises

directly with the load. Thus while, as has been already pointed out, the ratio of the rotary itself is practically fixed, the applied voltage to the slip rings can be varied and the D. C. voltage thereby changed.

Shunt excited rotaries are best adapted for lighting loads. The rheostat in the field circuit should be adjusted to give a minimum A. C. input at full D. C. load. The power factor will then be practically 100% for all loads and the delivered e.m.f. constant. Shunt rotaries are not adapted for cases where there are likely to be sudden and violent changes in the load as the delivered e.m.f. will fall due to drop in the whole system. Compound rotaries are therefore preferable, especially in railway

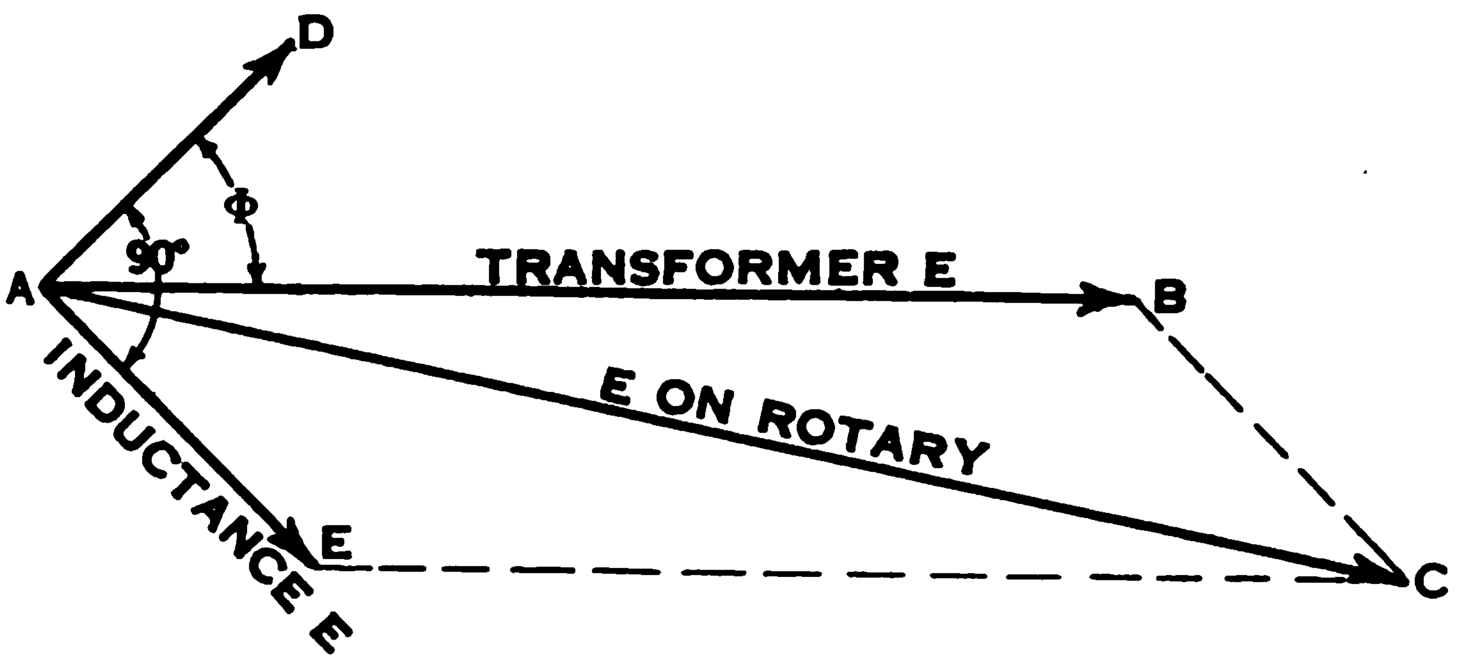


FIG. 920.

systems and other variable load work that involves a low load factor.

To sum up the features of phase control, the following facts may be stated:

1. A series winding on the rotary automatically changes the ampere-turns applied to the field.

2. Varying the field ampere-turns means varying the magnetizing component of the alternating current received by the slip rings, causing said current to lead when the ampere-turns are more than normal, Fig. 917, and lag when they are less than normal, Fig. 916.

3. The e.m.f. across the inductance L, Fig. 918, in circuit reduces the e.m.f. of the transformer arriving at the rotary when the current lags, Fig. 919, and increases the e.m.f. reaching the rotary when the current leads, Fig. 920.

4. The conditions for compounding in a rotary are:

(*a*) A series winding on the rotary connected to aid the shunt winding.

(*b*) Inductance in circuit between the A. C. generator and the rotary.

5. The series field on the rotary does not increase the D. C. e.m.f. directly as in a D. C. compound generator but indirectly through cooperation with inductance in the supply circuit.

To properly adjust the compounding of a rotary, proceed as follows: With a reactance capable of producing a variation of 15% of the transformer's voltage, from no load to full load inserted at *L*, Fig. 918, the shunt excitation of the rotary should

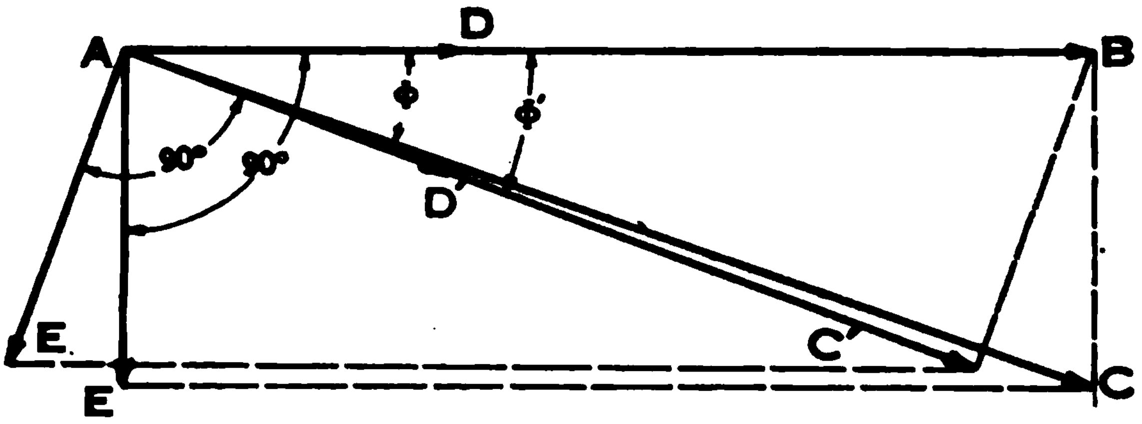


FIG. 921.

be adjusted by means of the field rheostat so as to bring about a lagging current of between 20 and 30% of full-load current at no load by under-excitation.

The series field should then be adjusted to give a slightly leading current at full load. Under these conditions the power factor will be approximately 40% lagging at 12.5% normal load and in the neighborhood of 98.5% leading at 150% normal load. These adjustments lower the e.m.f. impressed on the rotary at no load and raise it at full load enough to compensate for all losses in the system, and thus deliver a constant D. C. e.m.f. at all loads. The range of phase control is limited to about 4% above and 4% below the no-load and full-load D. C. voltage. It is not practical to over-compound as in D. C. generators.

It is obviously not possible to so adjust the excitation of a rotary that the power-factor will be 100% on both the transformer and the converter. Referring to Fig. 921, if the excitation for any given load is adjusted so that the current *A-D* is in phase with the transformer's voltage *A-B*, it will be out of phase with the voltage *A-C* at the rotary's rings by the angle Φ. If

the adjustment is made so that the current takes the position $A\text{-}D'$ in phase with the rotary's voltage $A\text{-}C'$, it will be out of phase with the transformer's voltage $A\text{-}B$ by the angle Φ'. The angles Φ and Φ' will increase with an increase of the inductance in the A. C. lines leading to the rotary's rings.

Control by Dial Switches. The second method of varying the voltage at the slip rings of a rotary is by means of dial switches connected to taps on the high-tension side of transformers. This plan is not much used, as the switching involved is complicated and the number of taps excessive. Moreover, there is danger of short-circuiting sections of the windings in altering the connections between adjacent taps.

Control by Induction Regulator. The third method of A. C. voltage control is by means of an induction regulator. This consists of a polyphase transformer in which the inductive relation of the primary to the secondary is changed by mechanically shifting the primary. It avoids the necessity of switching and gives a perfectly smooth variation of A. C. voltage.

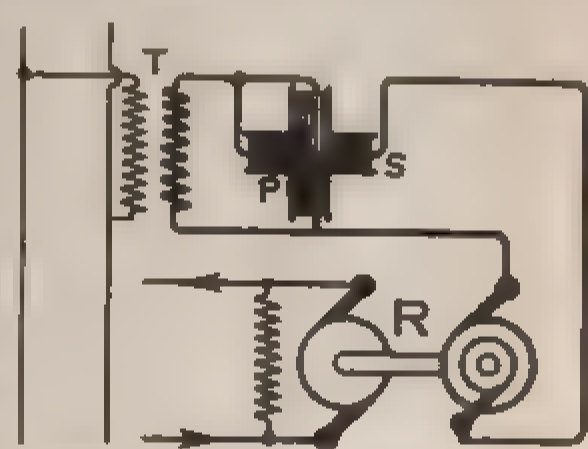


FIG. 922. Control of the D. C. voltage of rotary converter by means of induction regulator in the A. C. circuit.

Fig. 922 shows such a regulator in a simplified form for a single-phase rotary. Here current from the low-tension winding of the transformer T passes through the induction regulator on its way to the rotary. The secondary of the induction regulator, S, is in series between the transformer and the rotary while the primary P is in shunt therewith. The primary is excited at constant line voltage. By changing the position of the primary, the secondary voltage is changed in value and in phase relation with the line voltage with which it adds vectorily. The line voltage may therefore be raised or lowered by any amount within the capacity of the secondary e.m.f. As the secondary e.m.f. may be made to either buck or boost the line voltage, the total range in voltage reaching the rotary is equal to twice the voltage of the secondary winding. Thus if the transformer furnishes 300 volts and the secondary winding of the induction regulator furnishes

100, when the position of the primary is such as to cause these voltages to buck, the rotary receives 300 minus 100, or 200 volts. When the primary is shifted so as to cause these 100 volts to aid the transformer, the rotary receives 300 plus 100, or 400 volts. The usual range is about 15% above or below normal.

The rotation of the primary is effected by means of a small geared motor on top of the induction regulator. This motor is operated by alternating current controlled through the medium of a contact making voltmeter on the D. C. side of the rotary. If the load on the rotary increases, the voltmeter connects the pilot motor in circuit so as to move the primary of the regulator in such a direction as to raise the voltage. If the voltage on the D. C. is too high, the voltmeter puts the pilot motor in circuit

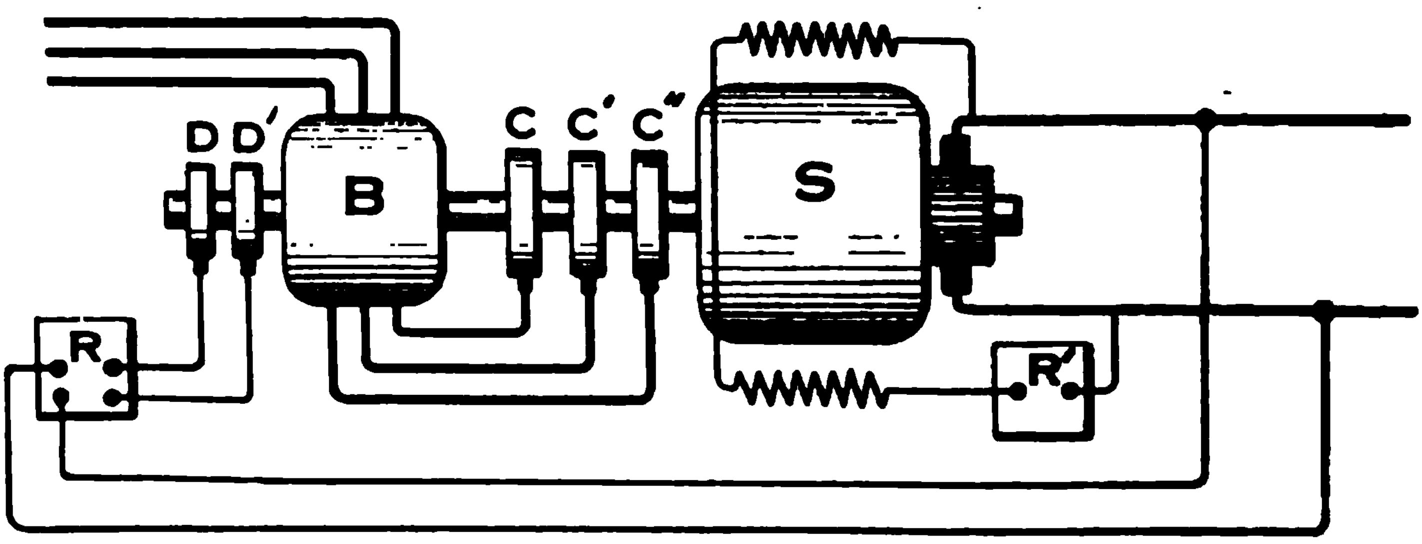


FIG. 923.—Control of the D. C. voltage of a rotary converter by means of a synchronous booster in the A. C. circuit.

so as to rotate the primary of the regulator in the reverse direction, and the voltage delivered to the slip rings is lowered.

Figs. 764 and 765, pages 79 and 80 illustrate the actual construction of a General Electric Induction Regulator. The disadvantages of the induction regulator method of control are high first cost, the large amount of floor space required, and the complication of wiring and control. Because of these disadvantages, this type of control has been largely superseded by the synchronous booster type.

A. C. Voltage Control by Synchronous Boosters.—This method consists in placing a small synchronous alternator on the same shaft with the rotary converter in order that it may run at synchronous speed, or the booster may be driven separately by a synchronous motor. Fig. 923 shows the usual arrangement. Here the A. C. supply is led through an external stationary armature of the booster *B* and thence to the slip rings *C-C′-C″*

of the rotary *S*. The D. C. end of the rotary supplies the D C. load and also the field of the rotary and the field of the booster. The excitation of the rotary is adjusted by the rheostat *R′*. The field of the booster revolves and contains the same number of poles as the stationary field of the rotary. It is supplied with current through slip rings *D-D′*. The excitation of the booster is adjusted by a reversing rheostat *R*. It is evident that by varying the excitation of the booster, or by reversing it, the voltage of the A. C. source may be increased or diminished on

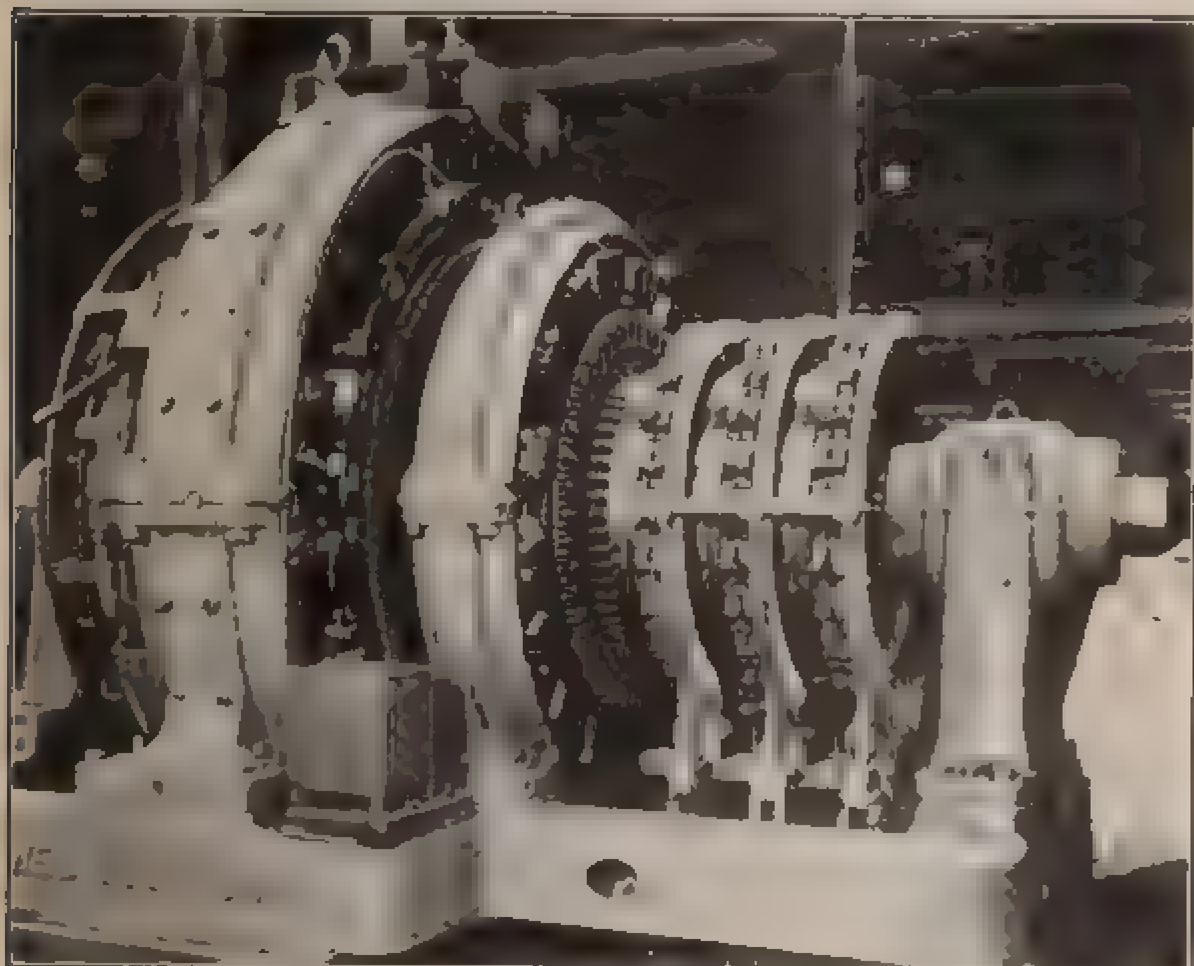


FIG. 924 —Westinghouse six phase synchronous booster type of rotary converter.

the rotary rings. If the A. C. supply furnished 250 volts and the maximum e.m.f of the booster was 50 volts, then with the booster's voltage aiding it the slip rings would receive 300 volts, while with its voltage opposing the supply, the slip rings would receive only 200 volts. A six-phase synchronous booster type of converter with revolving armature, manufactured by The Westinghouse Company, designed for 60 cycles and having a direct-current capacity of 8,000 amperes, is shown in Fig 924.

In **large units** the booster is usually of the **revolving armature** type and placed inside the main shaft bearings. In **small units**

it is usually necessary to place the booster outside the main bearings for mechanical reasons. In this case the booster is of the revolving field type.

If the rotary is provided with interpoles it is necessary with synchronous booster control to alter the ampere-turns on the interpoles when the excitation of the booster is altered or reversed. This is due to the fact that when the booster's voltage aids the line, the machine is a generator and absorbs power mechanically from the rotary to drive it. When its voltage opposes that of the line, it acts as a motor and aids in driving the rotary. The armature reaction of the rotary under these two extremes would therefore be different, and the interpole winding which takes care of this matter must be adjusted accordingly

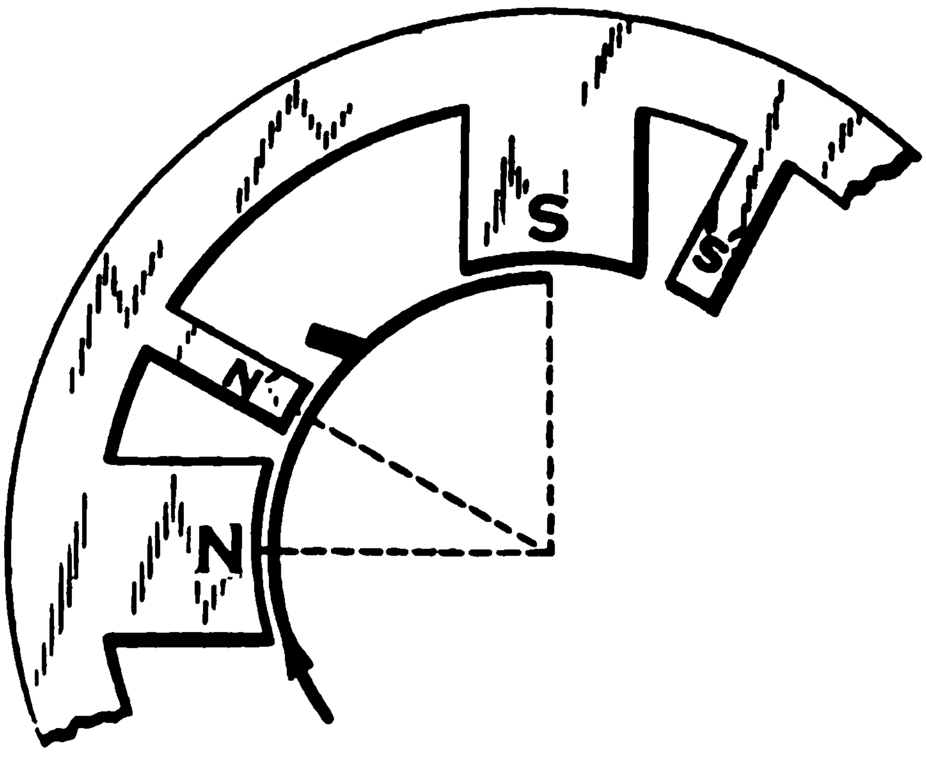


FIG. 925.—Split-pole converter.

A very satisfactory control has been obtained by a shunt winding over the usual interpole winding, either in series with the exciting circuit for the booster field, or by a rheostat controlled mechanically. These are then varied simultaneously and the desired interpole strength is assured at all times. This combination of a direct-connected booster and rotary is an advantage over the induction regulator in that it is simpler and requires less station wiring.

The Split Pole Converter.—It has been found, by dividing the field pole into sections and providing each with a separate winding, that the flux distribution across the pole face may thereby be changed. It thus becomes possible to obtain variable A. C. to D. C. ratios and control the D. C. voltage without

change in the A. C. voltage, thereby eliminating all devices corresponding to A. C. voltage control. It is possible to obtain variations by using a number of divisions of the field pole, but the simplest and most economical arrangement is to use two sections N and N', Fig. 925, which gives less complications and at the same time provides a sufficient amount of voltage control with less distortion of the alternating-current wave shape. In Fig. 926 A, B and C represent the poles excited for high, intermediate and low voltage, respectively. Starting with a condition of no excitation on the regulating poles, as shown in B, the

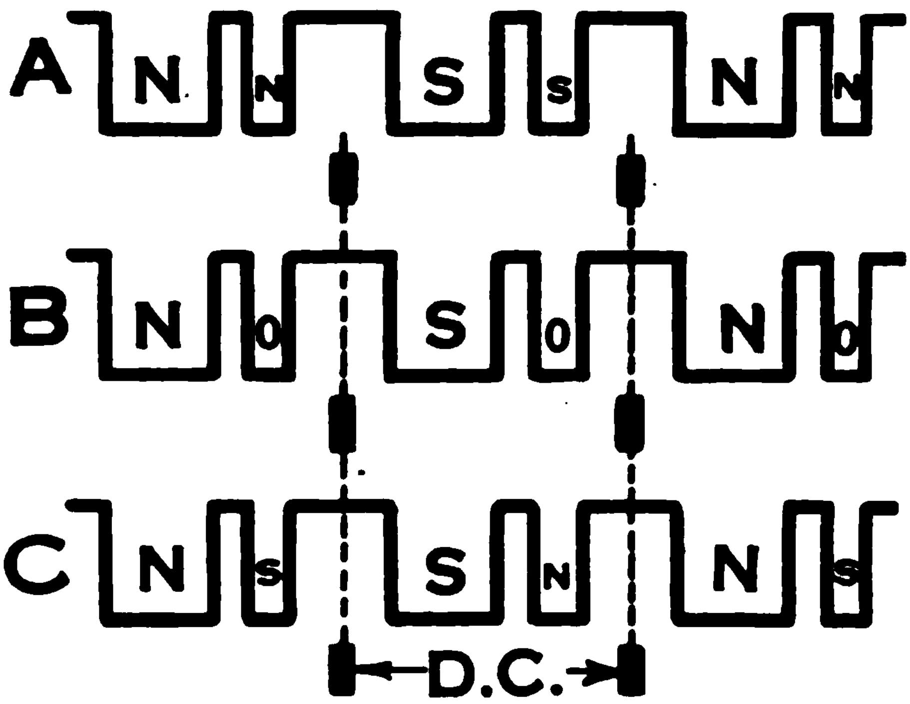


FIG. 926.

effective polar area is that of the main poles only. By gradually increasing the excitation of the regulating poles with current in the direction to give the same polarity as that corresponding to the main poles, as in A, and at the same time decreasing the strength of the main poles in direct proportion by means of a compensating winding, the effective length of the polar arc is gradually increased, without changing the total flux and power factor. As longer polar arcs cause a more peaked shape to the A. C. wave in a distributed winding, such as is used in all rotaries, and as the D. C. voltage is always the maximum value of the A. C. wave, the longer polar arc will give a higher D. C. voltage for a given effective A. C. voltage applied.

Starting again with no excitation on the regulating pole, as in B, and exciting this pole in the opposite direction as shown at C, at the same time adjusting the main pole strength by means of the compensating winding, the D. C. voltage will be reduced. This reduction is not dependent to any great extent upon the change in wave shape, but is chiefly due to the differential action

of the voltage generated by the two sections of the armature winding under the poles of opposite sign between adjacent brushes of opposite polarity. The voltage generated by the regulating pole flux opposes that generated by the main pole flux. Under this condition the D. C. voltage is not the same as the maximum A. C. voltage but is lowered in value for reasons explained.

Unfortunately commutation has proven difficult and rotaries of large capacity of this type are rather bulky and synchronous booster control is preferred.

Commutating Poles

The limit having been reached in the maximum output per pole in rotaries, it became desirable to introduce commutating poles. This resulted in a reduction in armature diameter for a given output. The commutation is then less of a limiting factor, as the interpole cares for this problem completely. The load factor may therefore be increased so that the full capacity of the rotary may be more nearly realized.

Commutating pole rotaries are smaller than those of the same capacity without such poles. The armature reaction in a rotary converter being only about 20% of that in a corresponding D. C. machine, the commutating poles carry only about one-third as many ampere-turns as D. C. generators for the same air-gap length. To provide for unusual disturbances, however, which might alter the A. C. to D. C. ratios, the air gap is made larger in a rotary than in a D. C. generator and the strength of the commutating pole greater than above suggested. Sparking at the commutator is still great with commutating poles, however, when starting from the A. C. end, and provision is therefore made for raising the direct-current brushes during the starting period. To provide excitation a special pair of D. C. brushes is employed.

Should a two-phase rotary be employed to supply a three-wire D. C. system, the armature is wound for 250 volts on the D. C. side and connected to the two outside wires. The neutral wire does not enter the rotary but is connected to the middle points *O-O*, Fig. 910, of both of the two transformers supplying the rotary, and thence in opposite directions through the windings. The magnetizing effect of this current on the cores would therefore be neutralized.

Interconnected Star Arrangement of Three Single-phase Transformers for Supplying Synchronous Converter

Should a Y-connected bank of transformers be employed to supply a three-phase rotary operating on a three-wire direct-current system, it might be supposed that the neutral wire of the three-wire system could be returned to the neutral or middle point of the Y on the transformers. If, however, the neutral wire were returned to the point *A* in Fig. 912, the direct current would flow successively in one direction through *A*1, *A*2 and *A*3. This current would on one alternation aid the alternating current in magnetizing the core, greatly increasing the magnetic flux. On the reverse alternation it would oppose the A. C. and materially lower the resultant flux. The magnetic circuit would thus be greatly unbalanced and the core losses increased. To avoid this difficulty the interconnected star arrangement of transformers has been devised. This consists in dividing thelow-tension winding of each transformer into two parts and connecting as in Fig. 927. One-half of phase 1 is in series with one-half of phase 3. The other half of phase 3 is connected in series with one-half of phase 2, while the remaining half of phase 2 is connected in series with the first half of phase 1. The resultant conditions are pictured in Fig. 928. If each half is capable of delivering 100 volts, then *D-F*, of phase 2, and *F-B*, of phase 1, will furnish a combined voltage equal to $\sqrt{3} \times 100$ volts or 173 volts, for these

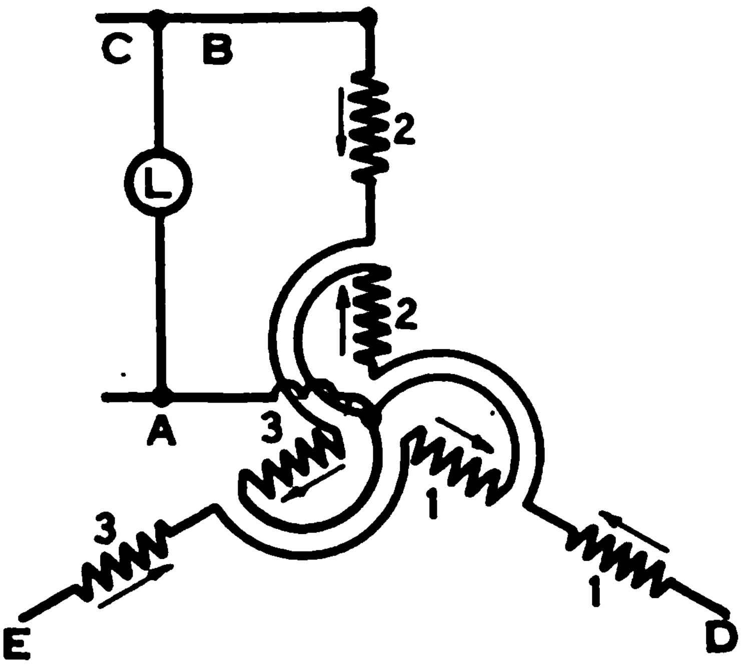


FIG. 927.—Theoretical connections of "inter-connected star" arrangement of transformers for three-phase rotary converters supplying three-wire direct-current system.

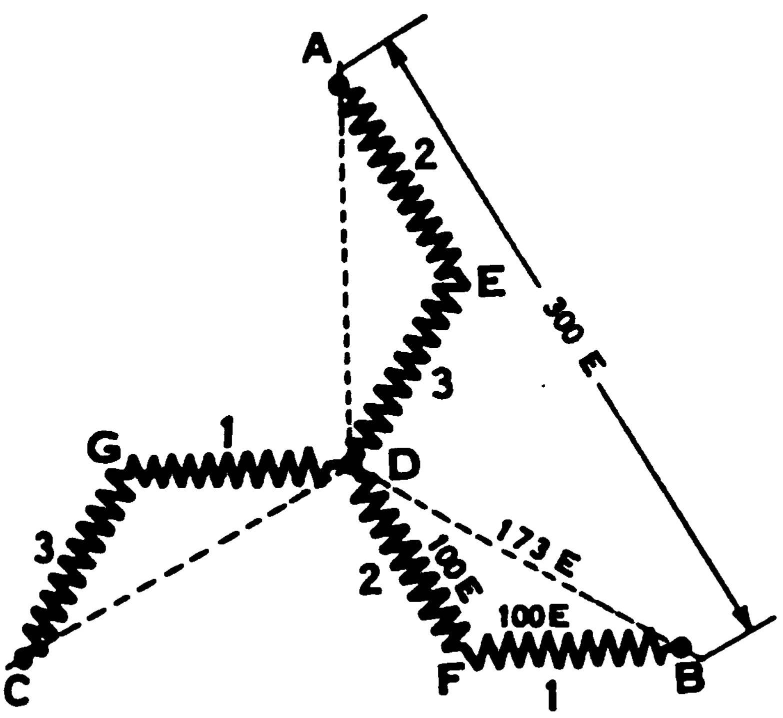


FIG. 928.—Relation of voltages in various sections of transformers arranged for inter-connected star.

two sections produce voltages 120° apart in phase. This resultant voltage of 173 is delivered in turn by *A-D* and *C-D*. When these resultants are combined in Y, the total voltage across *A-B* is $\sqrt{3}$ times 173 or 300 volts. As these voltages are obtained at a disadvantage the transformer must have a greater capacity when so connected, that is, the resultant voltage *D-B* is 30° out of phase with *D-F* and likewise 30° out of phase with *F-B*. The cosine of 30° is 0.866. To provide 100% voltage the capacity of the two sections would need to be $\frac{100}{0.866} = 115.5\%$ of what it would be if they were in phase. Thus the K. V. A. capacity of the three transformers for inter-connected star operation would each need to be 115.5% of that required for the ordinary star connection. The result of the interconnected star is to cause any direct current flowing over the neutral wire of the three-wire system to circulate in opposite directions in the two halves of the low-tension winding of any transformer. Thus each exactly neutralizes the effect of the other, and the magnetic effect on the core is as though no direct current whatever circulated in the transformer winding. Thus, suppose that there is a demand in the neutral wire *A*, Fig. 927, to supply current for the lamp *L* and this current flows through the lower half of phase 2, as shown by the arrow, thence to the middle point of the Y, out over the neutral wire *A*, through the lamp *L*, back over the wire *B* and thence downward over the other half of phase 2, thus neutralizing the magnetizing effect of that same current in the other half of the winding of the same transformer on its way out. As the point *C* is connected to the commutator, it swings successively into contact with *D* and *E*, thus the neutralization of the D. C. magnetization is effective in all three transformers.

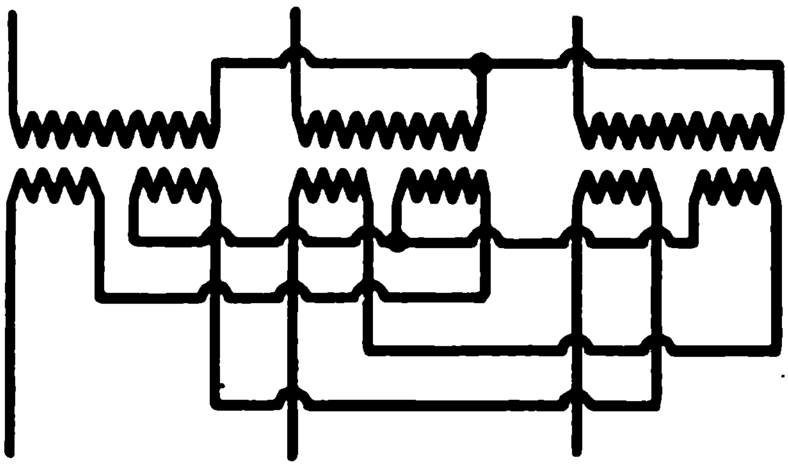


FIG. 929.—General arrangement of high-tension and low-tension windings of transformers arranged for inter-connected star.

Fig. 929 is a diagrammatic sketch showing the connection of transformers for interconnected star. The high-tension sides may be connected either in Y or Δ as preferred.

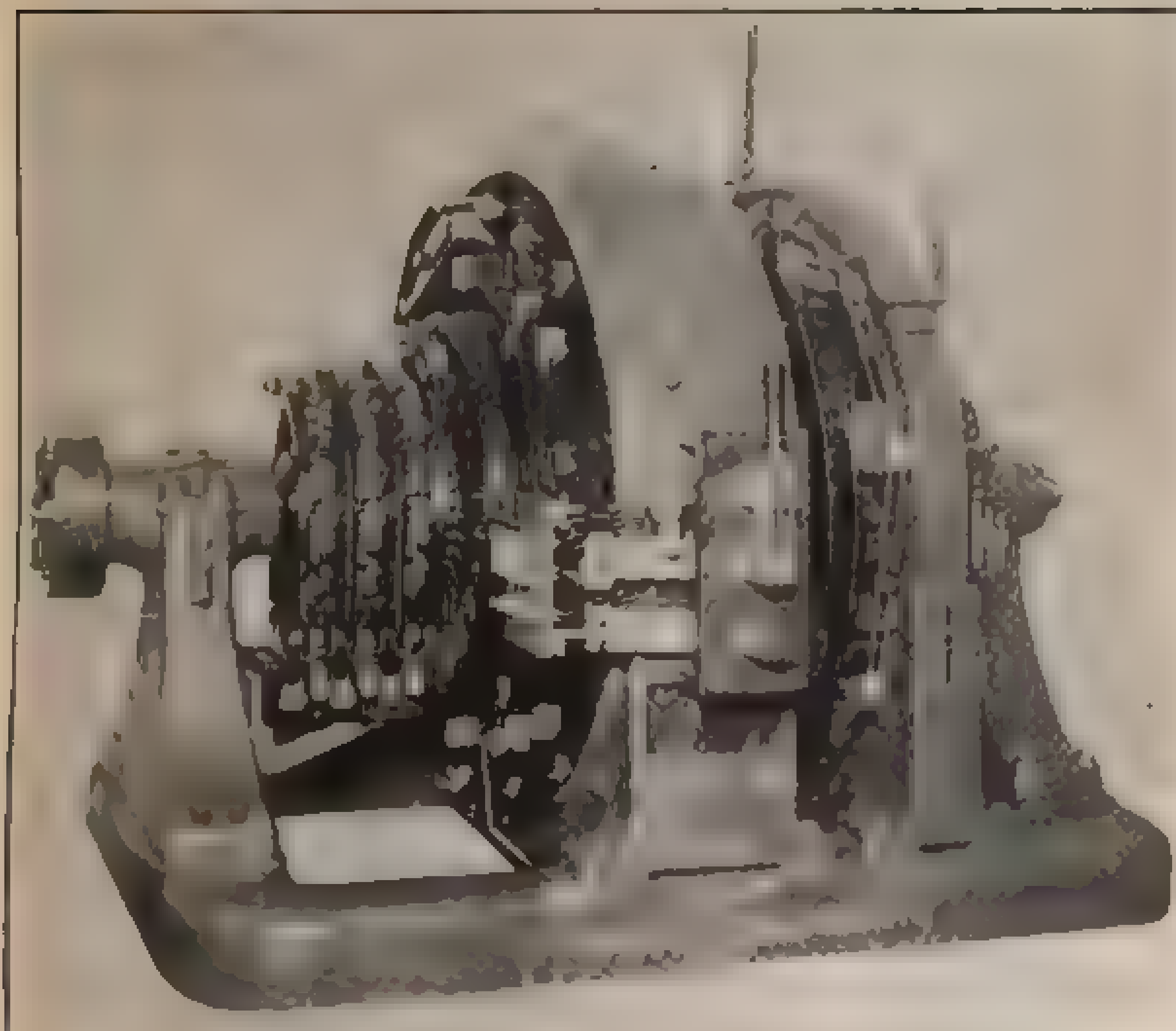


FIG. 930 General Electric, 1,000-K.W. synchronous converter

The general appearance of a modern General Electric synchronous converter is shown in Fig. 930. This is a 1,000-K.W., 8-pole, 900 r.p.m., 600-volt, 60-cycle, six-phase, compound-wound, commutating pole machine designed for railway work.

SECTION XVII CHAPTER III

SYNCHRONOUS CONVERTERS

D. C. VOLTAGE REGULATION

1 In how many and what ways may the D. C. e.m.f. of a rotary converter be regulated?

2 (*a*) Explain in detail the method of "phase control" of a rotary by external reactance in series therewith.

(*b*) Where is it used?

(*c*) What are its advantages?

(*d*) What are its limitations?

3. Where should shunt rotaries be employed? Why?

4. Where should compound rotaries be employed? Why?

5. In the absence of a power-factor meter how would you know when the intake of a rotary converter was obtained at 100 per cent power factor? How could this power factor be altered?

6. Explain the method of regulating the D. C. voltage of a rotary converter by quick break switches connected to taps on the high tension side of transformer. Where is this method used? What are its disadvantages?

7. Explain the construction and principle of operation of the "Induction Regulator" as used in regulating the D. C. voltage of a rotary converter.

8. Explain the construction and method of operation of the synchronous booster in connection with the regulation of the D. C. voltage of a rotary converter.

9. Explain the construction and principle of operation of the "split pole" rotary converter.

10. Explain the object of commutating poles on rotary converters. What are their advantages? When are they used?

11. Explain the "interconnected star" arrangement of three, single-phase transformers for supplying a synchronous converter. Where is it used? What is the advantage?

SYNCHRONOUS CONVERTERS

STARTING OF CONVERTERS

Starting from A. C. End.—There are three methods of starting rotary converters. First, from the A. C. end as a polyphase motor. For this purpose current is supplied by transformer *T*, Fig. 931, to a tap connecting through switch at about one-third line potential to the slip rings of the rotary converter *R-C*. The diagram shows a single-phase rotary, although it is understood that in practice all commercial rotaries are polyphase. The machine will start as a polyphase induction motor by means of the rotary field created by the armature windings. Although supplied with a low potential, it will come up to full speed, because the speed of an unloaded induction motor is determined

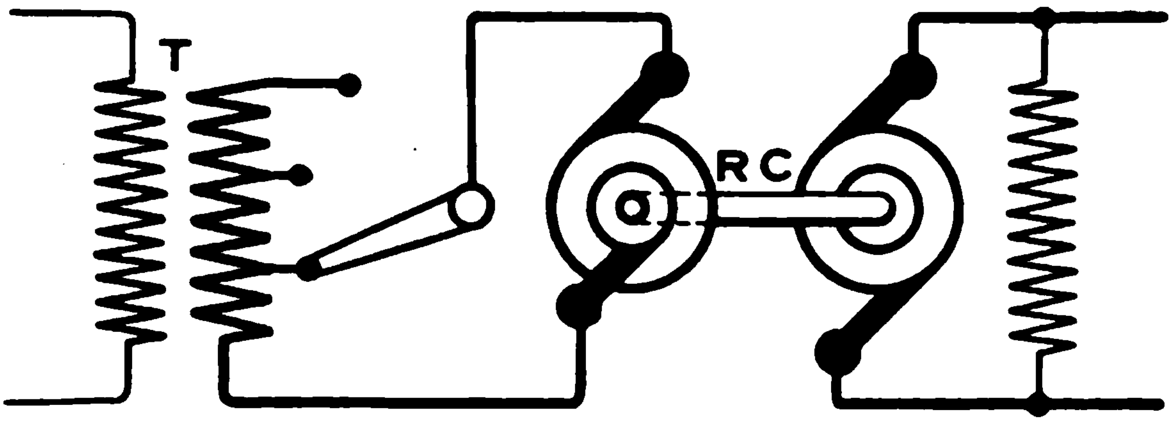


FIG. 931.—Starting rotary converter from A. C. end, as induction motor by current derived from potential taps on low-tension side of transformer.

solely by the frequency of the source of supply. If the field structure is provided with a cage winding, the machine starts much more readily as an induction motor. The field winding, when so starting, is usually disconnected from the D. C. brushes as shown by means of a switch *S* in Fig. 932. This is because the field coils act as the secondary of a transformer in their relation to the armature, which is the primary. As the relative motion between the rotating field produced by the armature with respect to the field coils is very high at the start, the induced e.m.f. in the field winding might be so high as to puncture and burn the winding out if the field circuit were closed. Therefore a **field break-up switch,** *S*, Fig. 932, is provided in the circuit which not only disconnects the field winding but subdivides it

into sections for the purpose of reducing the total voltage induced in any section. When the rotary has reached synchronism the field break-up switch is closed and a direct current flows from the commutator brushes through the field winding and causes the armature to "lock-in" to synchronism with definitely established field poles. The machine is converted, at this instant, from an induction motor into a synchronous motor. At the moment the field switch is closed, the poles of the armature may be slightly in advance of, or slightly behind the field poles of opposite sign. Depending on the initial impulse of the direct current in the field winding, when the switch is closed, the armature poles will be drawn forward or backward as it locks into step. It cannot be definitely foreseen what the polarity of the D. C. brushes will be at the instant the field switch is closed.

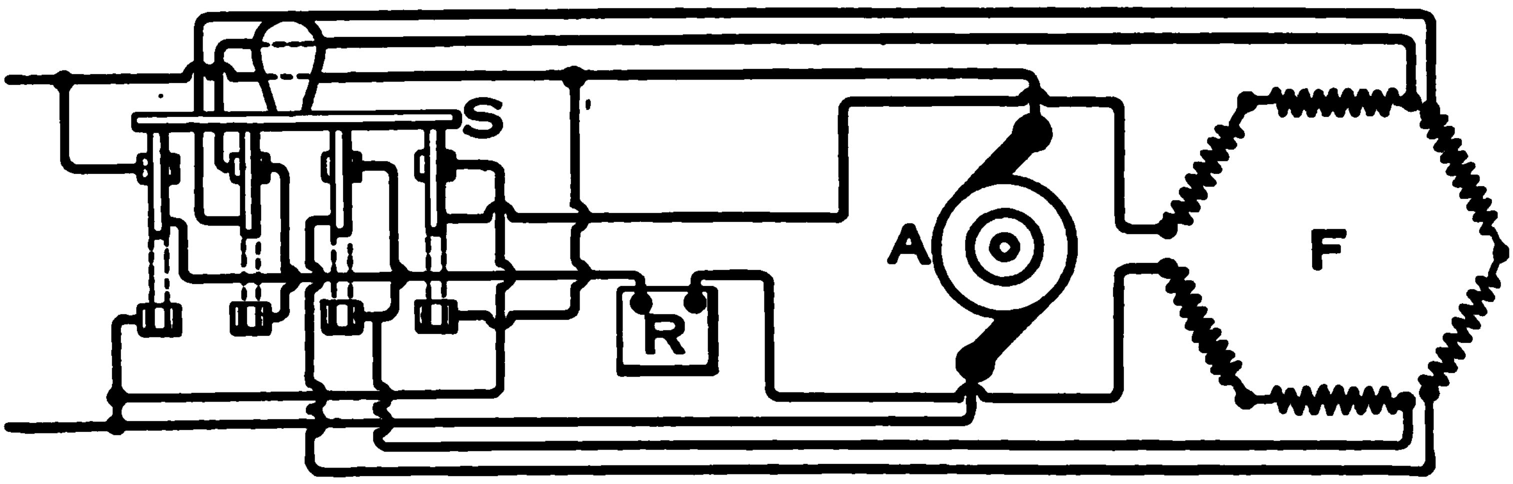


FIG. 932.—Field break-up and reversing switch for correcting polarity and protecting field of rotary converter when starting from A. C. end.

The upper brush may become positive and the lower negative or just the reverse, depending upon the relative movement of the armature at the moment of closing the switch. As rotary converters are usually operated in parallel with other similar machines in substations, the connections would be as shown in Fig. 933. Here it may be assumed that the rotary *R* is already running on the bus bars *E-F*, which have the polarity indicated. If now, when rotary *G* is brought up to speed and the field switch closed, the terminal *A* should be negative and the terminal *C* should be positive, it is obvious that the main switch across *A-B* and *C-D* should not be closed as the rotary *G* having reversed polarity would thus short-circuit the line. It is therefore necessary to reverse the polarity of the rotary. To do this the field break-up switch *S*, shown in Fig. 932, is thrown into the "down" position. This reverses the field winding with respect to

the D. C. brushes. The switch is held in this position for from five to eight seconds, during which the rotary is supposed to slip back one pole. It should then be thrown again into the "up" position, under which conditions the polarity should be reversed so that *A* would become positive and *C* would be negative. The proper polarity is indicated by a voltmeter connected across *A-C*. If the polarity is wrong, the voltmeter indicates backward. If the polarity is right, the voltmeter indicates in a positive direction. Up to this time the potential on the A. C. end, and therefore on the D. C. end, has been maintained at one-third normal. When it is found that the polarity is right, the A. C. tap on the transformer is raised to full potential. The

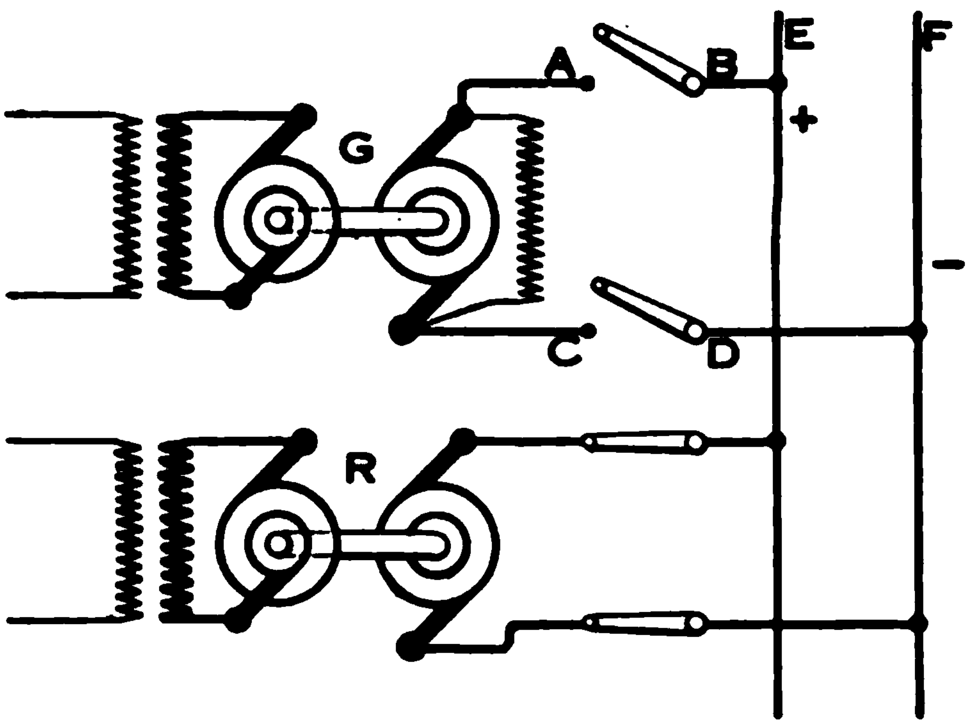


FIG. 933.—Switching connections for paralleling one rotary converter with another, already running.

main switch, *A-B*, *C-D*, may now be closed and the rotary *G* connected to bus bars in parallel with *R*.

One theory regarding the operation of the synchronous motor assumes that poles are manifested in the armature as indicated in Fig. 934, these poles reversing in sign at some point in the polar arc for a direction of rotation *A-B*, when the machine is running at synchronous speed. The polarity of the D. C. brushes and their relation to the A. C. wave is shown in full in this figure.

When the machine is started on the one-third voltage tap as an induction motor, it rises in speed in the direction *A-B*, Fig. 934, to practically synchronous r.p.m. or in some cases actually "locks" in synchronism with the field switch open. When the

field switch is closed in the running position, if the D. C. polarity is reversed as indicated by the reversed indication on the voltmeter, the reversing switch in the field circuit is thrown as shown in Fig. 935. The first tendency of the machine is to reverse the magnetism in its field poles, due to the reversed current in the field windings. This causes the armature to slip back to the position shown by the dot-dash line. At this point the D. C. brushes make contact at the zero point of the wave *A-B-C-D* and the field current becomes zero. The armature may not slip farther, because, if it assumes the position of the dotted wave, the polarity at the brushes would be reversed and that, coupled with the reversal of connections, would produce the

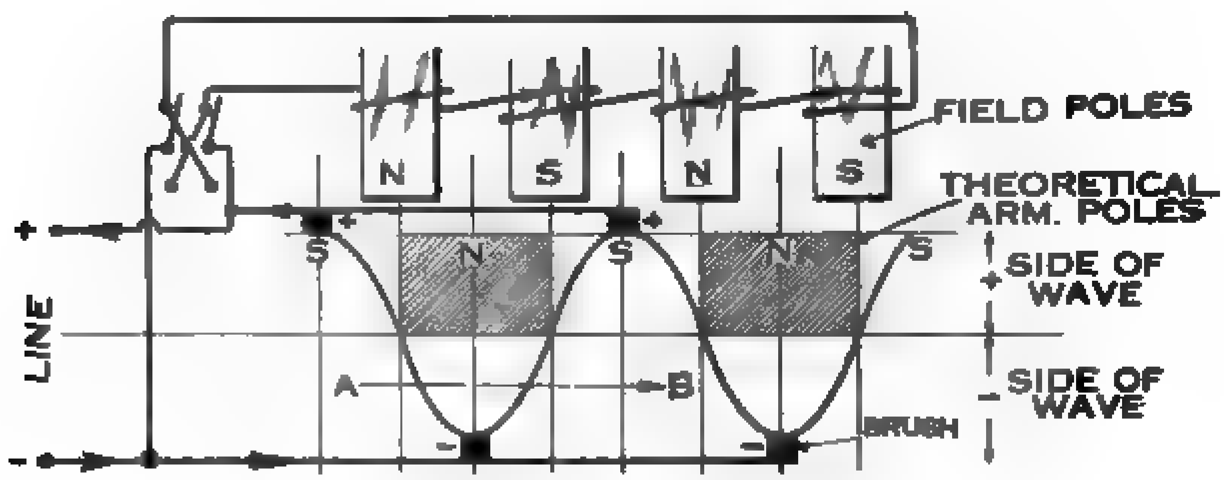


Fig. 934.

original polarity in the field and reversed polarity in the armature which will not give the required conditions for rotation. Should it slip back farther, due to low synchronizing power—i.e., large air gap, etc.—it will do so slowly with a pronounced tendency to "hang" in the position of the dot-dash wave. This will be indicated by the slow alternate reversals of the D. C. voltmeter. If the synchronizing power is great, the armature will remain as shown by the dot-dash line, cushioned, as it were, in the field If it tried to move either way, it would build up the field polarity in a direction opposing that motion. The voltmeter will now indicate a low value in the correct direction due to rotational losses dragging the armature a little back of the true center. If the field switch is now restored to the up or running position while the voltmeter indicates in the correct direction, the wave will slip to position of dotted line, the exciting current in the field coils will be reversed, now flowing in the direction of

the solid arrows, which will give the polarity indicated by *S′-N′*, and the polarity of the field poles will be reversed and conditions will be correct for rotation as shown in Fig. 935.

Throwing the A. C. switches on the two-thirds and full potential taps simply increases the voltage impressed on the A. C. rings and that delivered on the D. C. side without changing the r.p.m. or the phase relation. The direction of rotation of the armature is, of course, the same under all conditions.

Starting from the D. C. End.—The second method of starting a rotary is from the D. C. end as a shunt motor. The rotary *R*, Fig. 936, being in operation on the D. C. bus bars *L-M*, current may be taken to start the rotary *G* from the D. C. end. To do so the A. C. switch *A-B* must be open when the D. C. switch *K-H* is closed. The field rheostat *R* should be cut out so as to give the rotary a strong field. By means of a starting box *S-B*, the rotary is gradually brought up to speed. From the slip

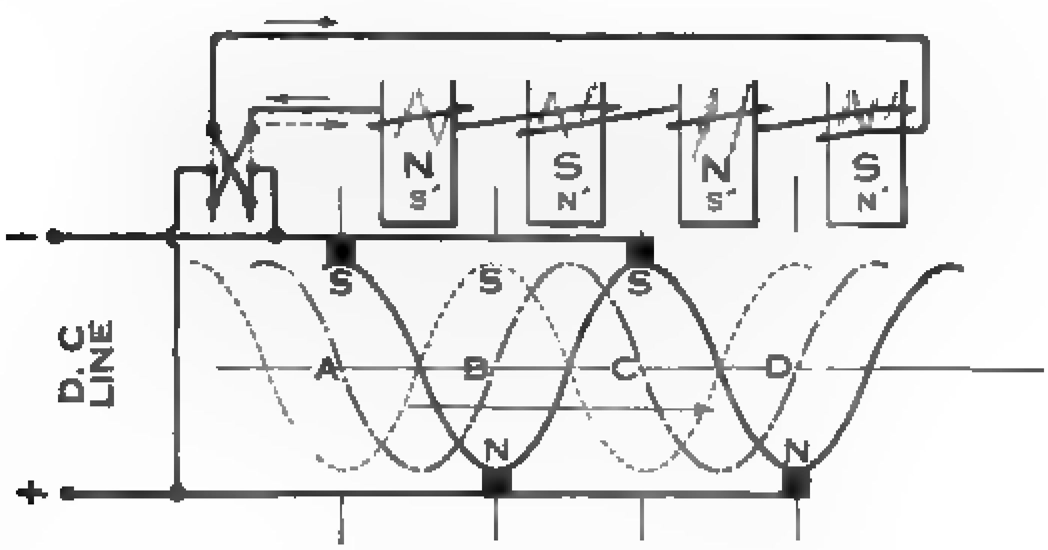


Fig. 935.

rings, *C-D*, an alternating e.m.f. is delivered to the terminals of the switch connecting the rotary to the A. C. supply.

Bridging the switches between the transformer and the rotary are the lamps *L-L*. There must be enough lamps in series to stand the combined voltages of the transformer and rotary. As the rotary comes up to speed the frequency of its alternating voltage delivered varies. The transformer *E-F* delivers a constant frequency. Due to the combining of these two e.m.fs., the lamps *L-L* will light when the two sources are in series, because their voltages are in addition, and will go out when the two sources are in opposition. As the speed and frequency of the rotary

changes, the phase relation of the rotary voltage and the transformer voltage alters. The lamps will therefore pulsate in candle power at a rate depending on the difference in frequency between the rotary and transformer. When the rotary comes into exact synchronism with the transformer the lamps will remain at a stationary candle power, but they may be bright, or dim, or out, depending on the phase angle of the two voltages. The proper time for placing the rotary in circuit with the transformer is when the two voltages are in direct opposition as shown by the arrows. Thus at a given instant the terminal E of the transformer must be positive when the terminal of the rotary, C, is likewise positive. The rotary's voltage thus corresponds to the counter e.m.f. of a motor, and the transformer voltage that of a source impressed upon it. As the rotary approaches

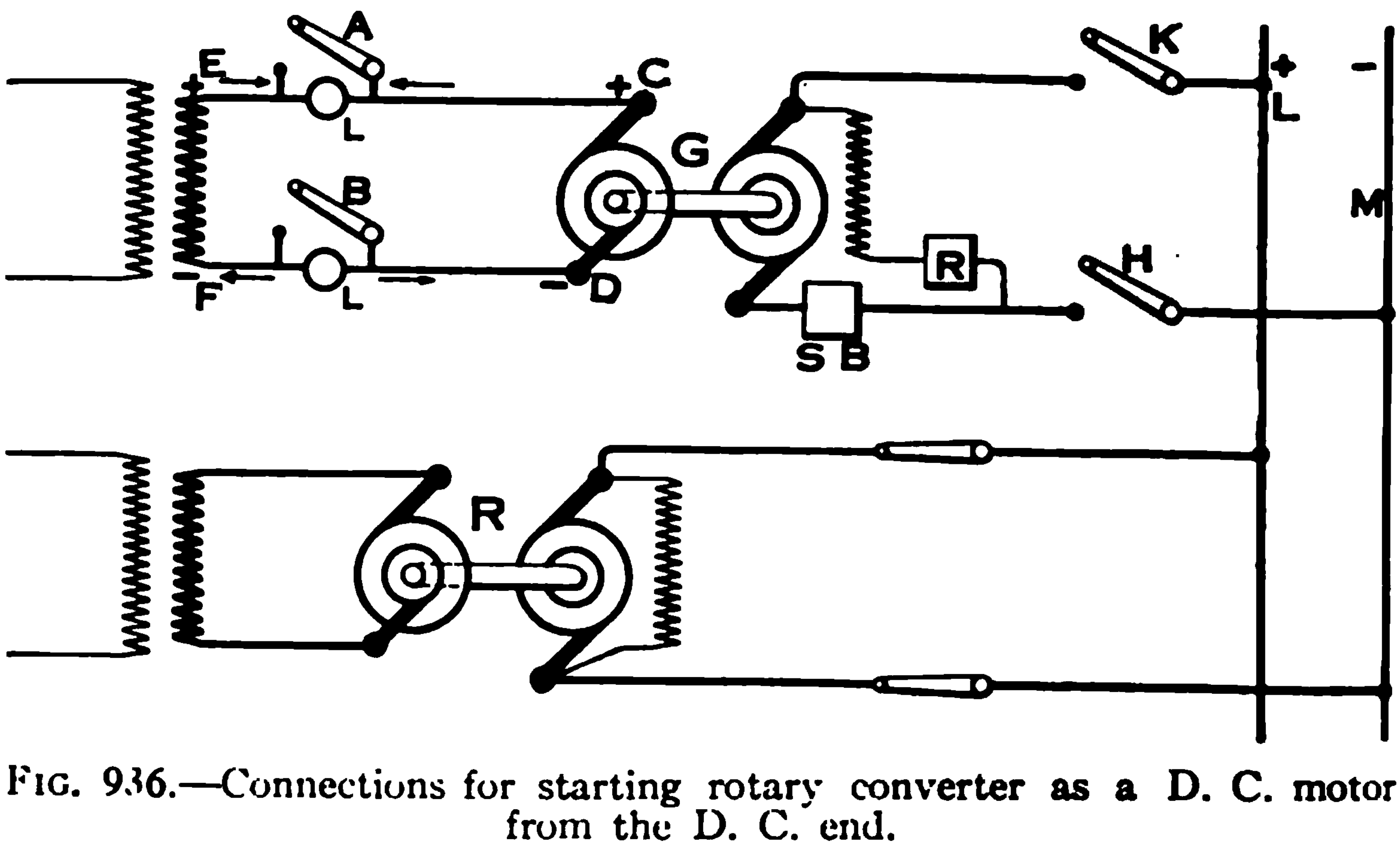


FIG. 936.—Connections for starting rotary converter as a D. C. motor from the D. C. end.

synchronism and the lamps flicker at a slower and slower rate, it is customary to close the switch A-B in the middle of a period of darkness, which indicates exactly the proper phase relation. If the lamps are pulsating rapidly when the switch is closed, a strong synchronizing current will flow between the transformer and the rotary, tending to accelerate or decelerate the rotary to bring it into step with the transformer. Care should be taken to see that the rate of pulsation is very slow when the switch is closed. The synchronizing current will then be reduced to a minimum. When the rotary has been connected on

the A. C. end, the starting box S-B on the D. C. end should be cut out and the field rheostat R adjusted to give a minimum A. C. input for the required D. C. load. Lamp synchronizing has in late years been replaced by the "synchroscope," which is more accurate and satisfactory than lamps. This device will be explained later.

Starting by Means of Separate Motor.—The third method of starting a rotary is by means of a separate starting motor. In Fig. 937 a separate induction motor M, usually direct-connected on one end of the rotary shaft and mounted on a bracket extending from the base frame, is employed to start the rotary and bring it to slightly above synchronism. The starting motor usually has one pair of poles less than the rotary in order that it may bring the rotary up to synchronous speed or slightly above. When so starting, the A. C. switch S, leading to the transformer, and the D. C. switch S to the bus bars should both be open.

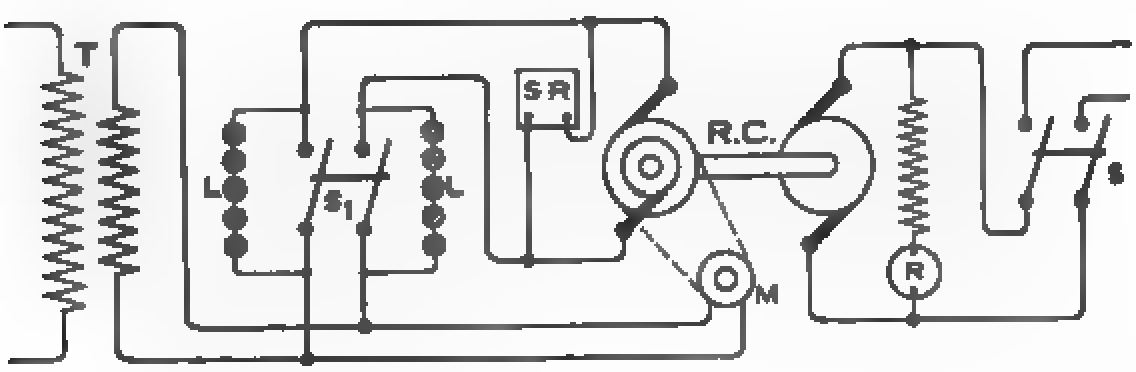


FIG. 937.—Connections for starting a rotary converter by means of a separate starting motor.

When the rotary has slightly exceeded synchronism a synchronizing rheostat S-R is connected across the A. C. brushes for the purpose of forming a load, which, in its reaction on the starting motor, brings the speed of the rotary converter down. Synchronizing lamps or a synchronoscope are employed to bridge the main switch, S, as before. When synchronism is indicated and the proper phase alignment is shown by the lamps becoming dark, the A. C. switch may be closed, after which the starting motor may be cut out and the D. C. switch closed, putting the rotary on the D. C. load. Large rotaries do not employ the synchronizing rheostat, but the variation in speed necessary to bring the rotary into exact synchronism is accomplished by the alteration of the field rheostat R. This varies the iron losses

in the armature of the rotary. In a large machine this variation is sufficient in its reaction on the starting motor to bring about the desired changes in speed.

With compound rotaries the D. C. circuit breakers should have auxiliary tripping coils energized from the A. C. side, so that if the A. C. breakers go out, the D. C. side will automatically open and prevent the rotary from motoring on the D. C. end. Otherwise the direct current reversing through the series winding would so weaken the field as to cause the rotary to run away. Some rotaries are designed with a centrifugal overspeed switch on the end of the shaft so connected to the D. C. breakers that if the speed of the rotary rises above normal the switch will open the breaker.

When rotaries are operated inverted—i.e., converting D. C. to A. C., a heavy inductive load will react powerfully upon the field magnetism. It will be remembered that a lagging current on the alternator weakens the field. With an inverted rotary the same thing happens, except that the rotary is at the same time a direct-current motor and a heavy lagging current may so seriously weaken the field flux as to cause the rotary to run at a dangerously high speed.

Compound rotaries should never be run inverted, as varying loads would cause widely varying speeds which would result in delivering a variable frequency.

SECTION XVII CHAPTER IV

SYNCHRONOUS CONVERTERS

STARTING OF CONVERTERS

1. Explain the method of starting a rotary converter from the A. C. end. What potential is employed? Sketch.

2. Explain the method of starting a rotary from the D. C. end. Sketch.

3. Explain the method of starting a rotary by means of a separate starting motor. Sketch.

SECTION XVII CHAPTER V

SYNCHRONOUS CONVERTERS

HUNTING IN ALTERNATORS AND CONVERTERS

An alternator, and a rotary converter connected with it, bear somewhat the same relation to each other as far as speed is concerned as an engine fly-wheel in which the driving force is transmitted through a flexible spiral spring to a second fly-wheel connected to it by means of this flexible coupling. The rotation of the second fly-wheel so connected to the engine will be steady only so long as the rotation of the engine fly-wheel is steady. If the engine fly-wheel momentarily increases its speed, the second fly-wheel will not maintain the same position relative to the first, as would be the case if the two wheels were rigidly connected. The inertia of the driven wheel will cause it to lag behind the first, as would be the case if the two wheels were connected by the spring, until the tension in the spring is great enough to overcome the inertia and momentarily increase its speed, bringing it back to its previous relative position. At the same time the tension in the spring will react upon the engine fly-wheel so that the speed of this wheel is momentarily decreased. If the inertia of the driven wheel is large, the reaction of the spring may carry it beyond its initial position to a point relatively ahead of that of the engine fly-wheel, in which case the tension in the spring will be reversed and will cause the second wheel to surge back again, thus starting an oscillation in the rotation of this wheel.

This condition is technically known as hunting. To set up this oscillation in speed three conditions are necessary:

1. A variation in the uniform rotation of the engine-driven fly-wheel.
2. A flexible connection between the two wheels.
3. Inertia in the second wheel.

A similar action takes place in the operation of electrical machines. If the load upon a power station alters, there will be some variation in the speed of the alternator. If the alternator is operating a rotary converter as a part of its load, the inertia of the rotary's armature will prevent it from instantly

following the alternator, and the resulting difference in the relative positions of the two armatures causes a change in phase positions of the alternator e.m.f. and the counter e.m.f. of the rotary. This change in phase angle causes a difference in the instantaneous values of the two e.m.fs. which brings about a surge of corrective current between the two machines. This current is equivalent to a tension in the spring between the engine and the driven fly-wheel. When the rotary's armature is behind the alternator the corrective current flows in such a direction as to accelerate its rotation and retard the alternator. The momentum of the rotary may be sufficient to carry it not only abreast of the alternator but relatively ahead. In this case the direction of the corrective current reverses as did the direction of tension in the spring coupling above referred to. This will simultaneously accelerate the alternator and retard the rotary's armature. In this way irregularity of the rotation of the rotary will be produced. This irregularity is called hunting.

To bring about hunting in a rotary three conditions must obtain:

1. Irregular rotation of the alternator.
2. A flexible connection in the shape of the electrical circuit between the alternator and rotary.
3. Inertia in the rotary converter.

The corrective currents between the two machines automatically tend to make the rotary follow the changes in speed of the alternator. How closely it actually succeeds in following them depends upon the design of the rotary. If the self-induction of the rotary armature is large, the corrective current for a given resultant e.m.f. will be small, and the force tending to change the relative positions of the alternator and rotary's armature will be less able to overcome the inertia, and the rotary's armature will then be sluggish in its action. It will not be able to follow the oscillation of the alternator, and the rotary will fall out of step and shut down.

If, on the other hand, the self-induction of the rotary armature is small, the force tending to change the relative position of the two machines will be great. The corrective currents will be large, the rotary armature will swing forward and beyond its proper position, and an oscillation will be set up as above.

When the self-induction is large and the corrective currents are small, the coupling is frail, as when a weak spring is used. If the self-induction of the armature is small, the corrective currents will be large, corresponding to a coupling with a strong spring. In addition to the self-induction of the armature, the impedance of the connecting lines and transformers restricts the corrective currents.

The corrective currents which circulate between the two machines due to the phase angle between their respective e.m.fs. at any instant increase the leading or lagging components of the total current. These leading or lagging components increase or decrease the strength of the field flux in both alternator and rotary, due to the magnetizing effect upon the armature windings. As hunting is an oscillation in the relative position of the rotary armature, a given pole being ahead of the alternator at one instant and behind it the next, the corrective currents due to this oscillation will be first in one direction and then in the other. The effect of this varying current is to strengthen one pole tip and weaken the other, when flowing in one direction, and reverse this action when flowing in the other direction, thus continually changing the distribution of magnetism over the pole face. This in effect causes the magnetic flux to continually shift back and forth across the face of each field pole. This action takes place in both alternator and rotary. A result of this shifting magnetic field is that it shifts the neutral line in the rotary which periodically brings the short-circuited coil in too strong a field for commutation and causes flashing at the direct-current brushes.

As hunting is always accompanied by a shifting field, a most effective method of preventing it is to employ dampers, in the form of heavy copper grids that surround each pole face and extend across it, usually imbedded in one or more slots.

Whenever the relative position of the alternator armature is changed by the corrective currents, the reaction of the induced currents in the grid tends to prevent this change. As long as the armature moves in exact synchronism with the alternator there are no currents induced in the grids. The grid acts like a cage winding in an induction motor. If the speed of the rotary alters, as it does momentarily when hunting, the powerful induced currents oppose the movement of the flux just as the induced current in a cage winding of an induction motor, which in their

reaction oppose the forward or backward slip. It must be noted that the eddy currents induced in the grid do not act as a constant opposing force to the corrective currents but as true dampers becoming zero whenever the rotational relation between the alternator and rotary is constant.

When several rotaries are connected to the same alternator, hunting in one rotary may cause trouble with the others if the lagging and leading currents due to the hunting are large enough to bring about serious variations in alternator voltage. Dampers on the alternator field poles help to control the corrective currents between the alternator and the rotary, the action of the dampers being identical with those on the rotary.

In alternators having partially closed armature slots the damper may be made in the form of a plate, *A*, Fig. 938. In re-

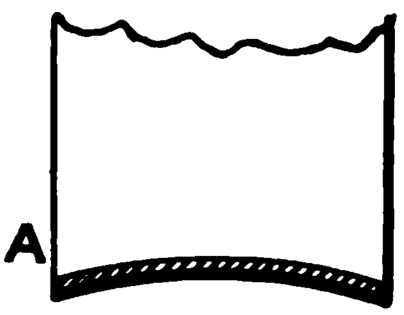


Fig. 938.

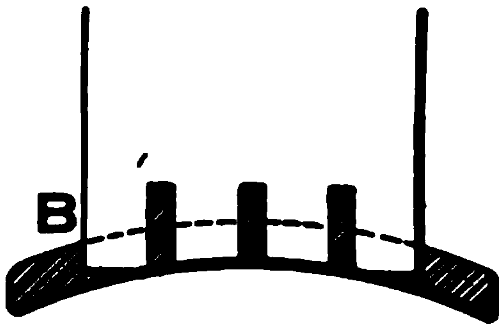


Fig. 939.—Electro-magnetic dampers or rotary converters.

volving armature machines the plate covers the face of the field pole. In machines where the field revolves the damper bridges the space between adjacent poles. It also serves in this case as a wedge to hold the field coils in place. In alternators with open slots and in rotary converters the dampers are of the grid type, surrounding the pole and extending through slots in the pole face, *D*, Fig. 939. This grid form of damper is better adapted to open slot machines because of the characteristic jumping of the field flux from one armature tooth to the next. This action would set up eddy currents in a copper plate which covered the entire pole and might increase the losses of the machine sufficiently to warp the plates seriously and loosen them from the poles. In self-starting synchronous converters the grids are all interconnected to form a complete cage winding.

SECTION XVII CHAPTER V

SYNCHRONOUS CONVERTERS

"HUNTING" IN ALTERNATORS AND CONVERTERS

1. What is "hunting" in a rotary converter? What causes it?
2. How may hunting be prevented in rotary converters? How does the remedy prevent it?
3. What forms of dampers are used on alternators and rotaries with partially closed slots. What style is used with open slots?
4. Where are dampers located in revolving field machines? Where are they placed in revolving armature machines?
5. What is an "inverted" rotary? What precautions should attend their use?

SYNCHRONOUS CONVERTERS

PHASING OUT OF CONVERTERS

When polyphase rotaries are first installed it is necessary to connect them to the main switches on the A. C. side so that when one phase is in alignment with the alternating source on the other side, all of the phases will also be in alignment. Thereafter it is unnecessary to synchronize more than one phase.

To obtain the proper sequence of phases when connecting a rotary to the switches the first time, it is necessary to "phase out." This means to test the circuits leading from the transformers furnishing the supply to the rotary itself, so that, when one pair of leads in one circuit is in phase with a corresponding pair of leads in the other circuit, all corresponding leads of the two circuits will be in phase. After this phasing out has once been accomplished it is only necessary thereafter to synchronize by means of a synchroscope or lamps on one phase of a polyphase rotary provided the connections have not been altered.

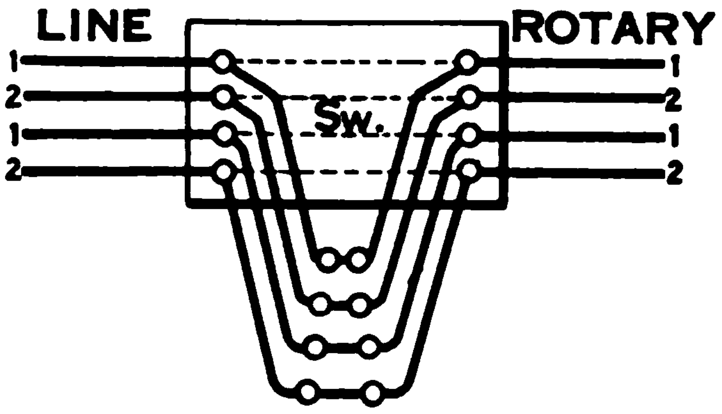


FIG. 940.—Connections of synchronizing lamps for two-phase converter.

In the few cases where single-phase rotaries are employed, it is obviously unnecessary to "phase out," for the synchronizing is accomplished between the source and the rotary on the one existing phase.

Two-phase Rotaries.—Two-phase four-wire rotaries may be tested out as follows:

First, determine the two leads belonging to one phase by a voltmeter. Those having normal voltage between them belong to one phase. Thus in Fig. 940, if line wires **1-2-1-2** come from two-phase transformers and the voltage across **1-1** is **180** volts and across 2-2 is likewise 180 volts, this would show that these lines represented the terminals of two separate transformers. On the four other lugs of the switch, *Sw.*, the four terminals coming from the slip rings of the two-phase rotary are connected.

They should also be tested so that 1-1 belong to one phase and 2-2 to the other phase. A series of lamps capable of standing the total voltage of one phase should be connected in each line across the opposite lugs of the switch terminals. Thus, when the voltage mentioned is impressed, each of the two lamps in series in the circuit shown should be capable of standing at least 90 volts; 110-volt lamps could be used. If the rotary voltage is high, potential transformers may be used across opposite lugs in place of the lamp bank, the low-tension side of the transformer connecting to a single lamp.

The rotary should now be started by running it from the D. C. bus as a direct-current motor or by means of a separate starting motor. It should be excited to normal voltage and operated at about synchronous speed. If the lamps do not all become light and dark together, interchange the main leads of one phase on one side of the switch, leaving the lamps connected to the same switch terminals. The lamps should now fluctuate together. The rotary is in proper phase to be connected to the transformer by closing of the main switch across the lamp banks when the lamps are in the middle of a period of darkness.

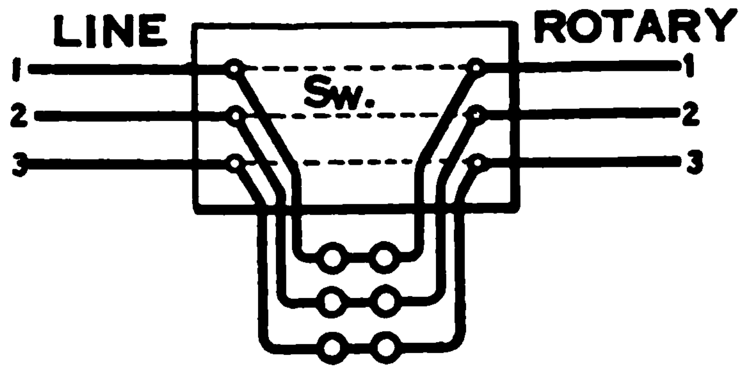


FIG. 941.—Connections of synchronizing lamps for three-phase converter.

Three-phase Rotaries.—To test a three-phase rotary, the three leads from the low-tension side of the transformer which supply the rotary are connected to the lugs on one side of the switch as in Fig. 941. The three terminals from the rotary are connected to the three opposite lugs. No care need be taken as to the order in which these lines are connected on the opposite sides of the switch. Across opposite switch lugs a series of lamps should be connected as shown. The number of lamps in each line should be sufficient to stand the entire voltage between any two wires as in the two-phase connections.

The rotary should be started as before and excited for normal voltage and run at about synchronous speed. If the lamps do not all become bright and dark together, it indicates a reversal of phase rotation—that is, the relative directions of rotation of the

source of supply and the rotary are opposite. The remedy is to interchange any two main leads on one side of the switch, leaving the lamps connected to the same switch terminals, after which the lamps should all fluctuate together. The source of supply and the rotary are in phase in the middle of a period of darkness.

Six-phase Rotaries.—The six-phase **diametrical** connection is the most widely used for rotaries. As the voltage is generally low, reducing transformers for the lamps are not often required. Across the opposite lugs of the main switch in Fig. 942 a series of

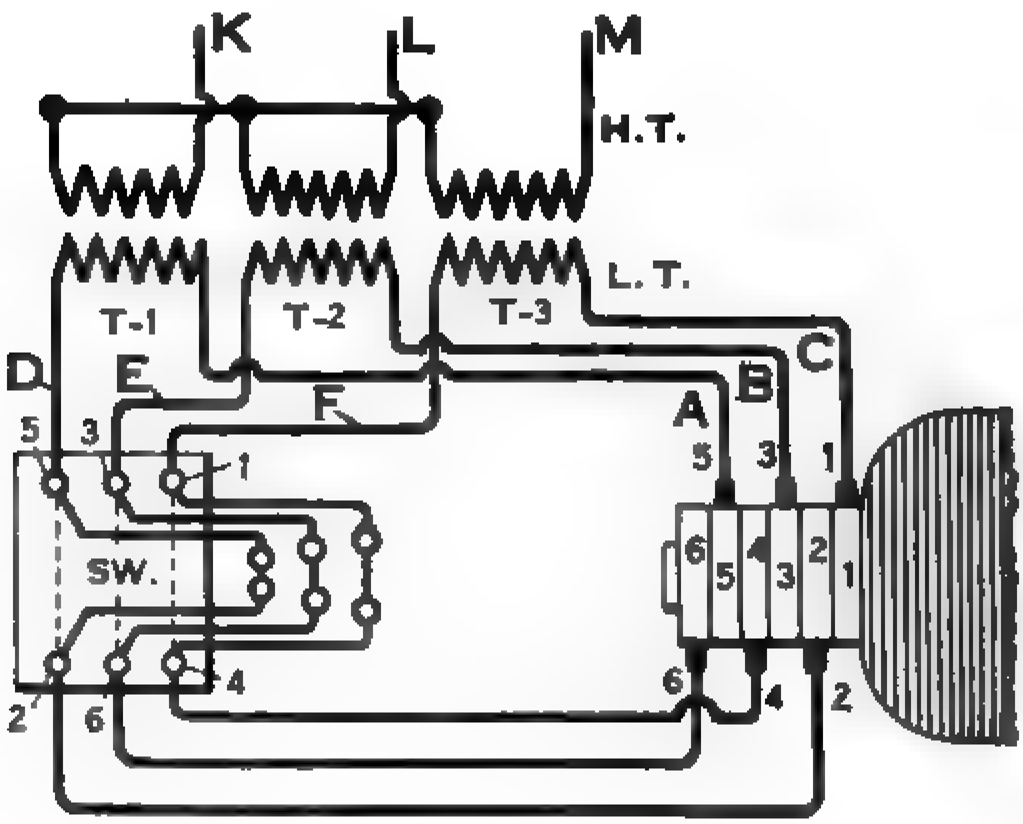


Fig. 942—Connections of synchronizing lamps and transformers for six-phase converter.

lamps should be connected, the total voltage on the lamps in each circuit being twice the diametrical voltage of the rotaries. If the rotary is used for the three-wire lighting system and supplies 250 volts, the virtual voltage on the A. C. side is approximately 72% of this amount, or 180 volts. The lamps in each series must then be capable of standing 360 volts.

First, the leads from the three transformers, *T*1-*T*2-*T*3, should be separated into two groups having one lead from each transformer in each group. Thus *A*-*B*-*C* may be in one group and *D*-*E*-*F* in the other group. By means of a voltmeter or a lamp bank these leads may be tested out or separated, provided cur-

rent is supplied to the high-tension winding. The test should show all leads in one group insulated from each other. If convenient, see that all three leads in one group connect to corresponding terminals of the transformer; thus *D-E-F* being derived from the left-hand terminals, presumably all positive at one instant, and *A-B-C* from the right-hand terminals, all relatively negative at the same instant. It is not necessary that the groups be so arranged. A reversal of one of the transformer connections can readily be corrected later.

Second, connect all leads in one of these groups, say *A-B-C*, to the slip rings of the rotary 5-3-1.

Third, connect all leads in the other groups, *D-E-F*, to the switch lugs numbered 5-3-1.

The six consecutively numbered slip rings in the rotary are supposed to be tapped into the armature winding in the manner shown in Fig. 943, 60 electrical degrees apart. If the diametrical voltage, say across 1-4, is 180 volts, the voltage between successive slip rings 1-2 will be one-half of the diametrical voltage (for 1-2 is the same as 1-7) and 1-2-7 is an equilateral triangle. This would be 90 volts, or 35% of the D. C. voltage.

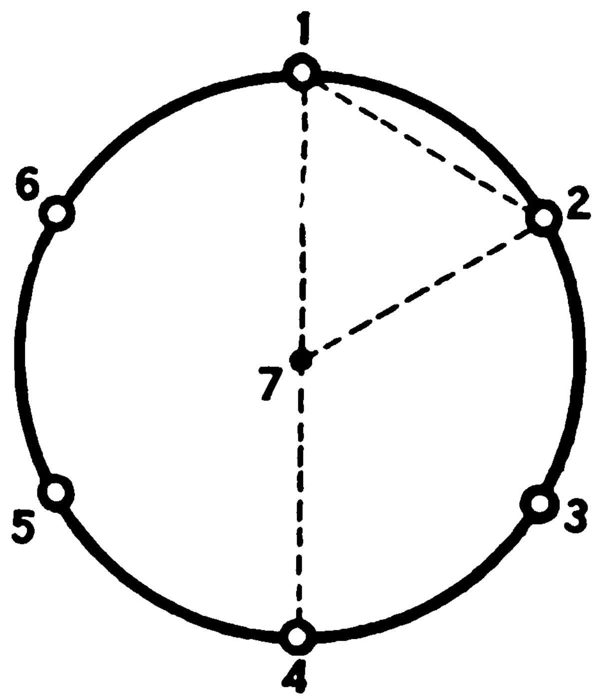


FIG. 943.

Fourth, connect the other three rotary terminals 6-4-2 to the switch lugs 6-4-2.

Fifth, the series of lamps previously referred to should now be placed across opposite switch terminals.

The **sixth** step is to test for continuity of circuits. To do this all the A. C. brushes should be raised from the slip rings. The main switch should then be closed. A series of lamps the same as those across the main switch terminals should now be placed between brushes 1 and 4, between 3 and 6, and between 5 and 2. This bridges the gap in the terminals of the circuits for each of the three transformers. The lamps should all light to show that the circuits are complete.

Seventh, open the main switch *S-W*, and put down all the brushes on the slip rings. Bring the rotary to approximately

synchronous speed and excite to normal voltage. The lamps may now fluctuate in four different ways.

1. The lamps may all grow bright and dark together. This indicates that the connections are correct. No change is necessary.

2. The fluctuations of the lamps may follow each other at regular intervals. This indicates a reversal of phase rotation. Remedy: interchange leads 1 and 3, also 4 and 6, at the rotary terminals, or if more convenient interchange any two three-phase high-tension leads, such as *K* and *L*, supplying the transformers. In any case the lamps must all fluctuate together.

3. Two of the lamp circuits may fluctuate together and the third in exactly opposite phase. This indicates a reversal of the secondary of a transformer. Remedy: interchange the leads of the transformer which connects to the lamp circuit that fluctuates out of step with the other two. When corrected, all of the lamps must fluctuate together.

4. The three lamp circuits may become bright in rapid succession and then pass through an interval when all are dim. This indicates a combination of difficulties in 2 and 3. Remedy: interchange the secondary leads of the transformer which connects to the circuit that fluctuates between the other two. Also interchange, at the rotary terminals of the switch lugs, leads 1 and 3, and 4 and 6. The lamps should then all fluctuate together.

SECTION XVII — CHAPTER VI

SYNCHRONOUS CONVERTERS

"PHASING OUT" OF CONVERTERS

1. Sketch and explain the method of "phasing out" a three-phase rotary converter, before connecting to line. When would connections be indicated wrong? When would they be indicated right?

2. Sketch and explain the method of "phasing out" a two-phase rotary before connecting to line. When would connections be indicated wrong? When would they be indicated right?

3. Sketch and explain the method of "phasing out" a six-phase diametrical rotary before connecting to line. When would connections be indicated wrong? When would they be indicated right?

SYNCHRONOUS CONVERTERS

MISCELLANEOUS TYPES OF RECTIFIERS

The Mercury Rectifier.—Consider a vacuum glass tube, Fig. 944, containing electrodes A and B, the latter of mercury, connected to a source of alternating current. The resistance of the circuit is so high that practically no current will flow. The apparatus may even be heated so hot that the mercury boils and the tube fills with mercury vapor at high pressure and still no appreciable current will flow. In fact, mercury vapor, either hot or cool, is considered a poor conductor of current. If, however, the electrical pressure on these electrodes is increased to about 25,000 volts the resistance suddenly breaks down and a current will flow. If this current is in the direction from A to B, the mercury at B will be vaporized and this vapor will fill the bulb. The current passes in the form of an arc, traveling on the conducting vapor of mercury. Part of the electrical energy is absorbed in vaporizing the mercury, which immediately condenses upon the walls of the bulb and flows back into the well in the bottom, only to be vaporized over again. The distribution of potential is approximately 4 volts drop at the surface of the electrode A, 6 volts in the vapor, and 4 volts at the surface of electrode B. If the current ceases to flow for even a small fraction of a second, the original resistance will be reestablished and it will require 25,000 volts to break it down again. Investigation shows that the most of this resistance seems to be concentrated at the surface of the negative electrode. If means can be provided for maintaining the flow of a current into the negative electrode, it will continue to pass, encountering very little resistance. A commercial form of mercury rectifier is illustrated in Fig. 945. Here current from a transformer, T, at 110 or 220 volts, leads to an auto transformer F. Movable contacts, X-X, adjusted by means of a dial switch, connect two wires, P-P', to electrodes A-B, sealed in a

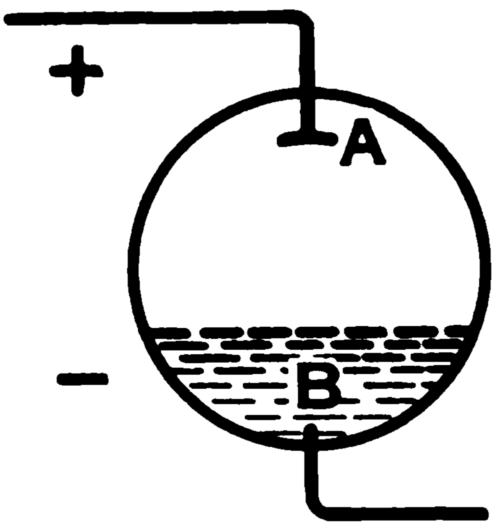


FIG. 944.

vacuum bulb containing a well of mercury, *M*, at the bottom, which constitutes the negative electrode. A special starting electrode *S* is sealed in just above the mercury negative and connects through a current limiting resistance, *R*, with the wire *P'*. A storage battery to be charged by the rectified current is connected to the electrode *C* and to the middle point of the auto transformer *F*. The alternating e.m.f. cannot pass between the electrodes *A*-*B* because of the high resistance encountered. If, however, the tube is tilted until the mercury *M* comes in contact with the electrode *S*, a current will flow from the auto transformer through the starting resistance and pass from *S* to *C*.

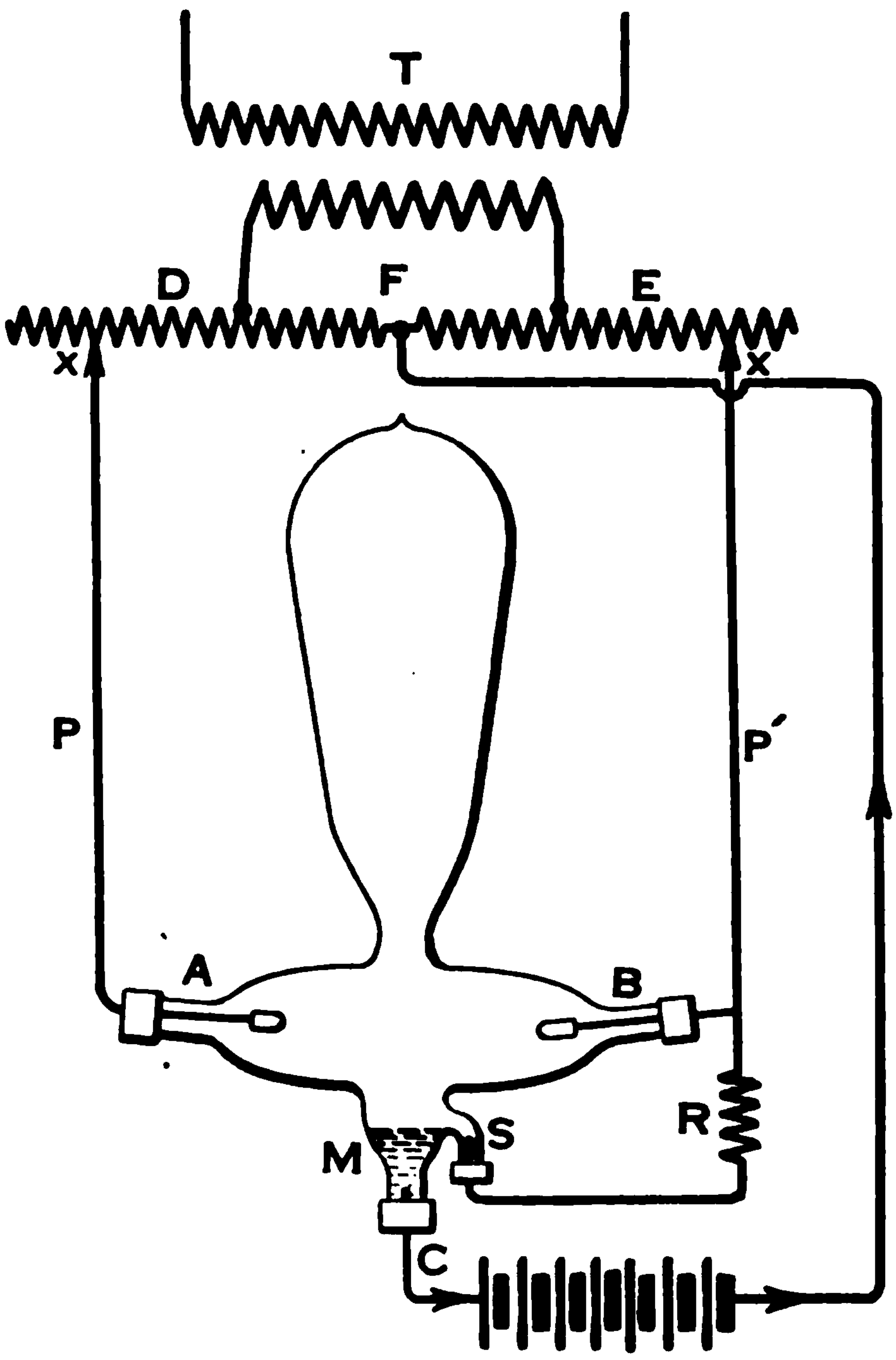


FIG. 945.—Single-phase mercury rectifier for charging storage batteries.

As the tube is righted the mercury breaks from the electrode *S*, starting an arc. The current flowing into the mercury breaks down the negative electrode resistance. Thereafter, so long as the current flows into *M* it will only require about 15 volts to force current either from *A* to *M* or from *B* to *M*. Should the

current cease, however, for the one-millionth part of a second, the high negative electrode resistance would again appear and current would cease to flow. One of the objects in the use of the auto transformer is to prevent this interruption. The transformer possesses considerable reactance. The current flowing through the storage battery must find its way back to the A. C. source either through the winding *D* or *E* of the auto transformer. The rectified current is pulsating in character, as in

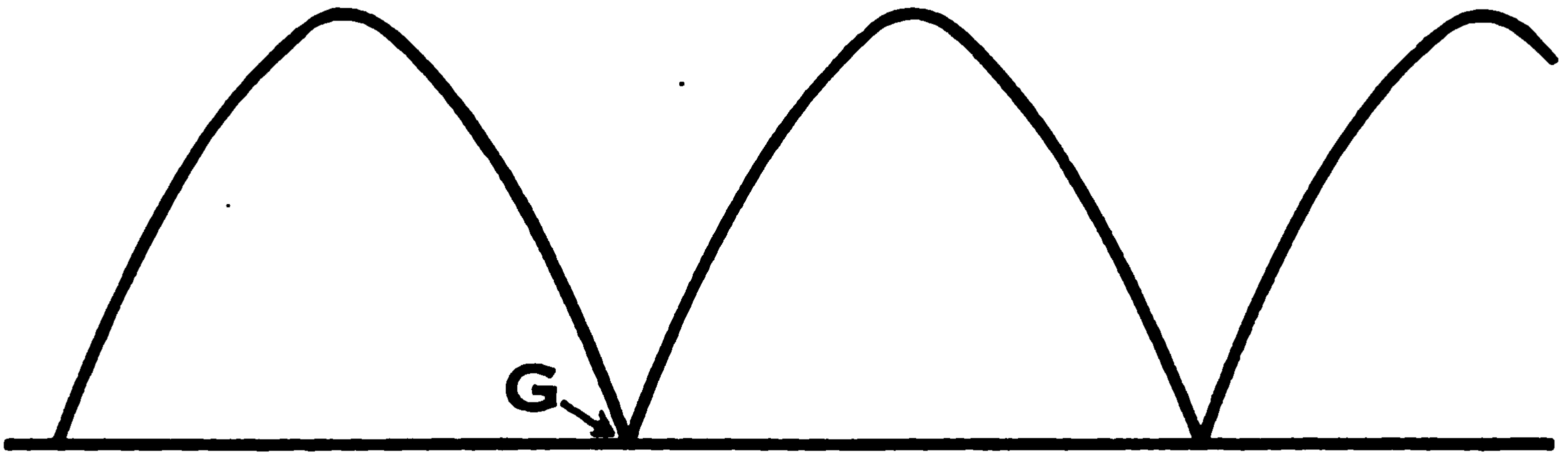


FIG. 946.

Fig. 946. Now unless special precautions were taken, when the A. C. wave reached the zero point, *G*, the rectifier would go out, and the high negative electrode resistance would be reestablished. The auto transformer prevents this, for the pulsating wave of current induces in the winding of the auto transformer an e.m.f. of self-induction which not only is opposed to the rise of the current but also to its fall. Thus when the wave from the electrode *A* tries to die out, as at the point *G*, the self-induc-

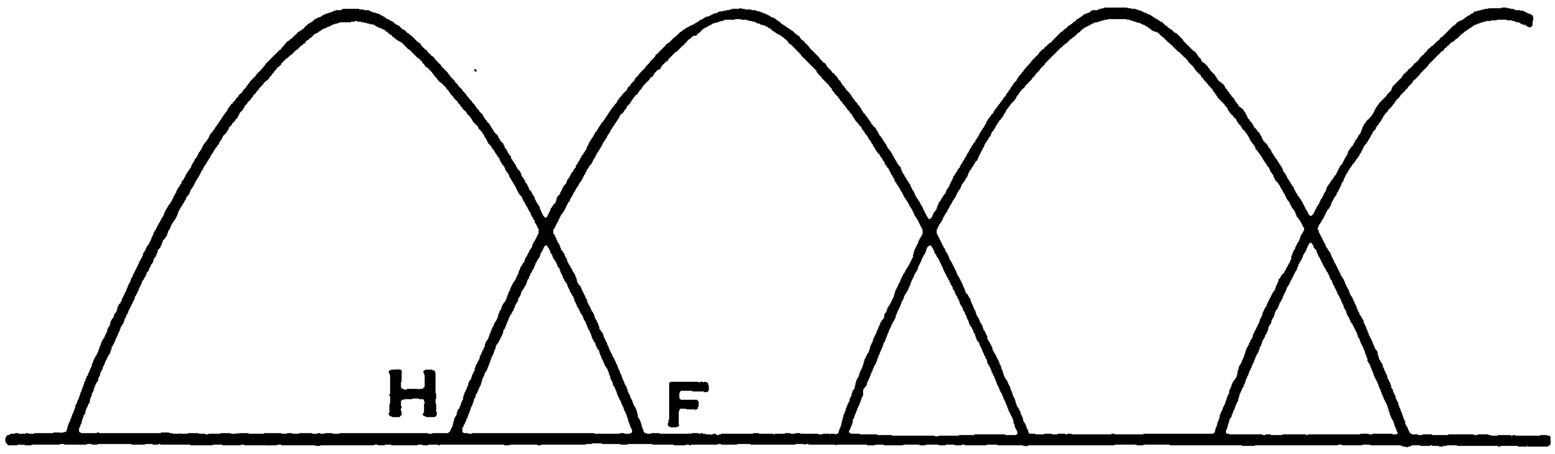


FIG. 947.

tion keeps it going as in Fig. 947, prolonging it to the point *F*, during which interval the current from the electrode *B* will have started, say at the point *H*. The result is that the waves of current are caused to overlap each other instead of being allowed to simultaneously reach the zero point. The greater the amount

of **reactance** in the circuit, the **less** will be the **variation** in the ripple of the **D. C. wave,** although the **height** of this wave will be **lowered.** The **less** the **reactance** in the circuit the **higher** will be the **D. C. wave,** although the **less** will the successive impulses **overlap** and the more readily will the rectifier go out of action. By shifting the points *X-X*, Fig. 945, the D. C. e.m.f.

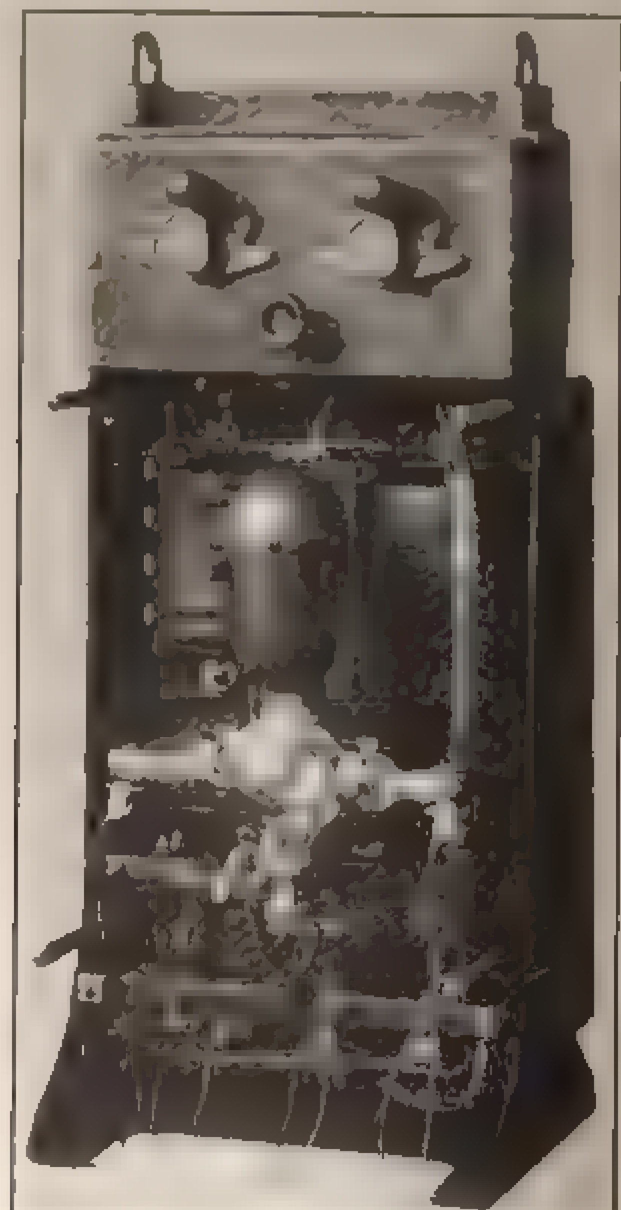


Fig. 948. Westinghouse, 30-ampere mercury rectifier.

may be altered from 20% minimum to 52% maximum of the A. C. voltage. The alternating current ranges from approximately 44% minimum to 56% maximum of the direct current. As the voltage loss in the rectifier is practically constant, the efficiency varies with the D. C. voltage delivered. A loss of 15 volts with a delivered e.m.f. of 100 means a loss of 15%, but this same fixed loss of 15 volts only means 1.5 per cent if the delivered voltage is 1,000.

A rectifier delivering 30 amperes from a 220-volt source, 60 cycles, has an efficiency of from 75 to 80% with a power factor of about 90%. These rectifiers possess an inherent regulation of about 6 to 8%. That is, as the counter e.m.f. of the batteries on charge rises, the e.m.f. charging them also rises from 6 to 8%. The life of this tube is about 400 to 800 hours.

A mercury rectifier for battery charging manufactured by the Westinghouse Company is shown in Fig. 948. This is their Type

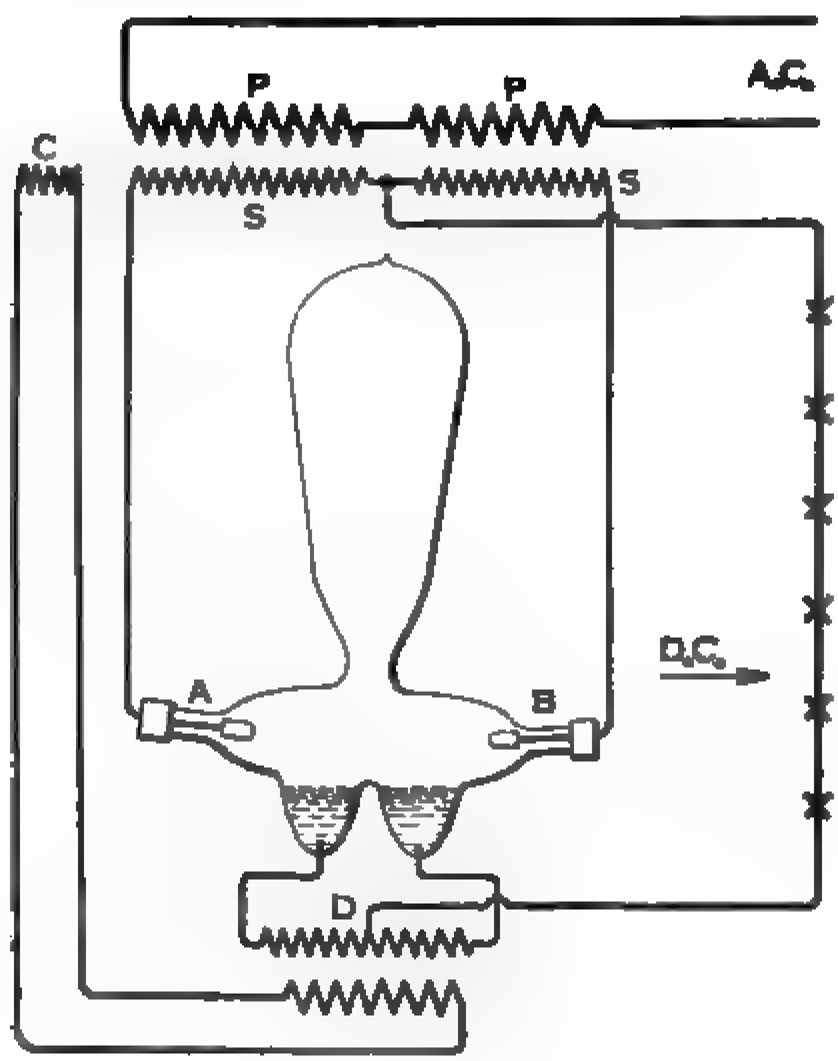


Fig. 949.—Single-phase mercury rectifier for series lighting circuits.

AA outfit, having a capacity of 30 amperes. It is provided with an electro-magnet for tilting the bulb, thus permitting automatic starting. In case the line voltage is interrupted, the outfit stops operation, but will restart when the voltage is restored. It will care for the charging of either 20 or 44 cells of lead storage battery from a 220-volt line.

For rectifying the current for series arc lighting circuits the arrangement shown in Fig. 949 is used. The alternating-current

supply energizes a regulating transformer with the primary sections *P-P* and the secondary sections *S-S*. The terminals of this secondary are connected to the electrodes *A-B* of the mercury rectifier. In the bottom is a mercury well connecting to the secondary of a starting transformer *D* employed to break down the negative electrode resistance. The primary of this transformer is energized by an additional coil *C*, carried on the regulating transformer. The current from the regulating transformer passes through either the electrode *A* or *B*, thence through the mercury negative and by either path to the middle tap, *D*, of the starting transformer and thence to the series of arc lamps, whence it finds its way back to the middle of the regulating transformer. This current is usually only 4.5 amperes or 6.6 amperes. The rectifying bulb can therefore be made quite small. As the voltage is high, the efficiency is quite high. The bulb is usually immersed in oil to assist in cooling. The life of these bulbs on high voltage circuits is usually from 10,000 to 14,000 hours. The object of rectifying the current for arc lighting circuits is that much higher efficiency is obtainable from a direct-current arc than from an alternating-current arc. The passage of the current through all mercury rectifiers causes the production of an electric arc. This arc raises the mercury to the vaporizing point, so that the globe is filled with mercury vapor. As this vapor strikes the cool surface of the bulb it condenses and runs back into the mercury well at the bottom, where it is vaporized over again.

The electric valve action of the mercury arc is not confined to mercury alone. Practically all electric arcs exhibit a rectifying tendency to a greater or less degree. The mercury arc is the most successful.

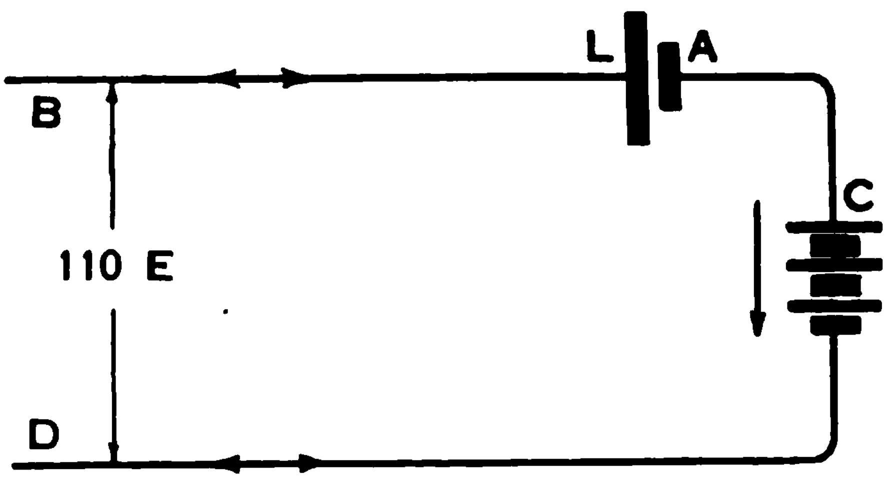


FIG. 950.—Single-cell electrolytic rectifier.

The Electrolytic Rectifier.—Another interesting type of electric valve is the electrolytic rectifier. This is known by various names, but the principle in all is the same. It consists essentially of a vessel containing a solution of ammonium phosphate or simply borax. In this solution are placed two electrodes, one of lead, *L*, Fig. 950, and one of aluminum, *A*, The surface of the lead plate should be made approximately ten times that of the

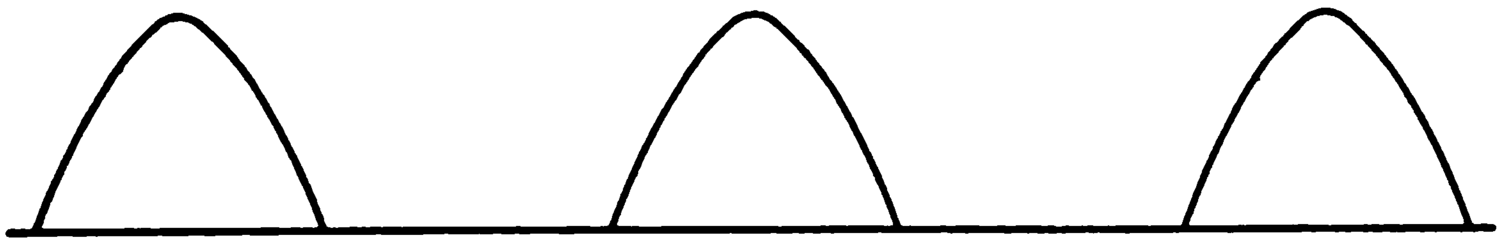


FIG. 951.

aluminum. If a current from an alternating source, *B-D*, is passed through such a device in series with a storage battery *C*, the following results will be observed: The current will flow readily from the lead plate, *L*, to the aluminum plate, *A*, and charge the battery. When, however, current tries to flow in the reverse direction from the aluminum plate to the lead plate, there is deposited on the lead plate a film of phosphate of aluminum which creates an enormous resistance and shuts off prac-

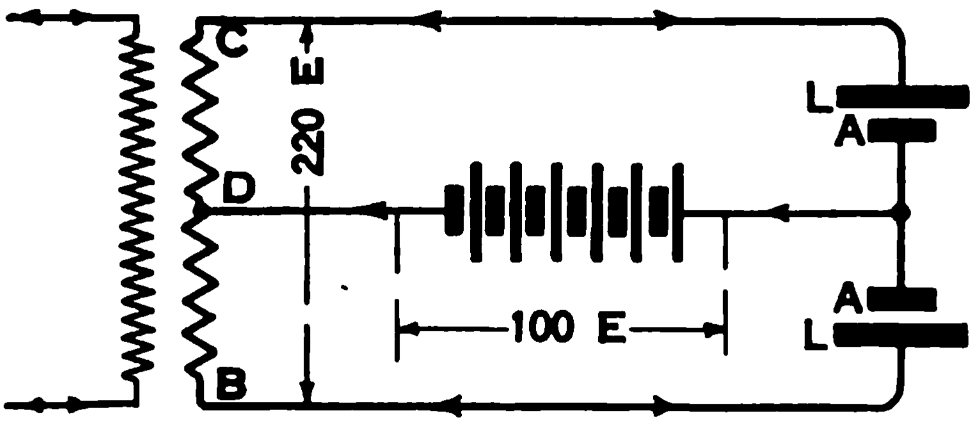


FIG. 952.—Two-cell electrolytic rectifier.

tically all further flow of current in that direction. This valve action gives the disjointed direct-current impulses shown in Fig. 951, the reverse alternation being wiped out entirely. If two such cells are used, wired as shown in Fig. 952, the lead electrodes being connected to the secondary terminals of a transformer, a storage battery being connected between the aluminum plates and the middle point of the transformer, an alternating current can flow from either terminal *B* or *C* of the transformer, through the storage battery, returning to the middle point, *D*, of the transformer. A reverse impulse, however, through the battery,

is impossible because the current cannot flow from aluminum to lead. This arrangement uses both impulses of the A. C. wave, and a battery would be charged in half the time that would be required with one rectifier. The voltage available, however, is only one-half of that of the source. By using four cells wired as

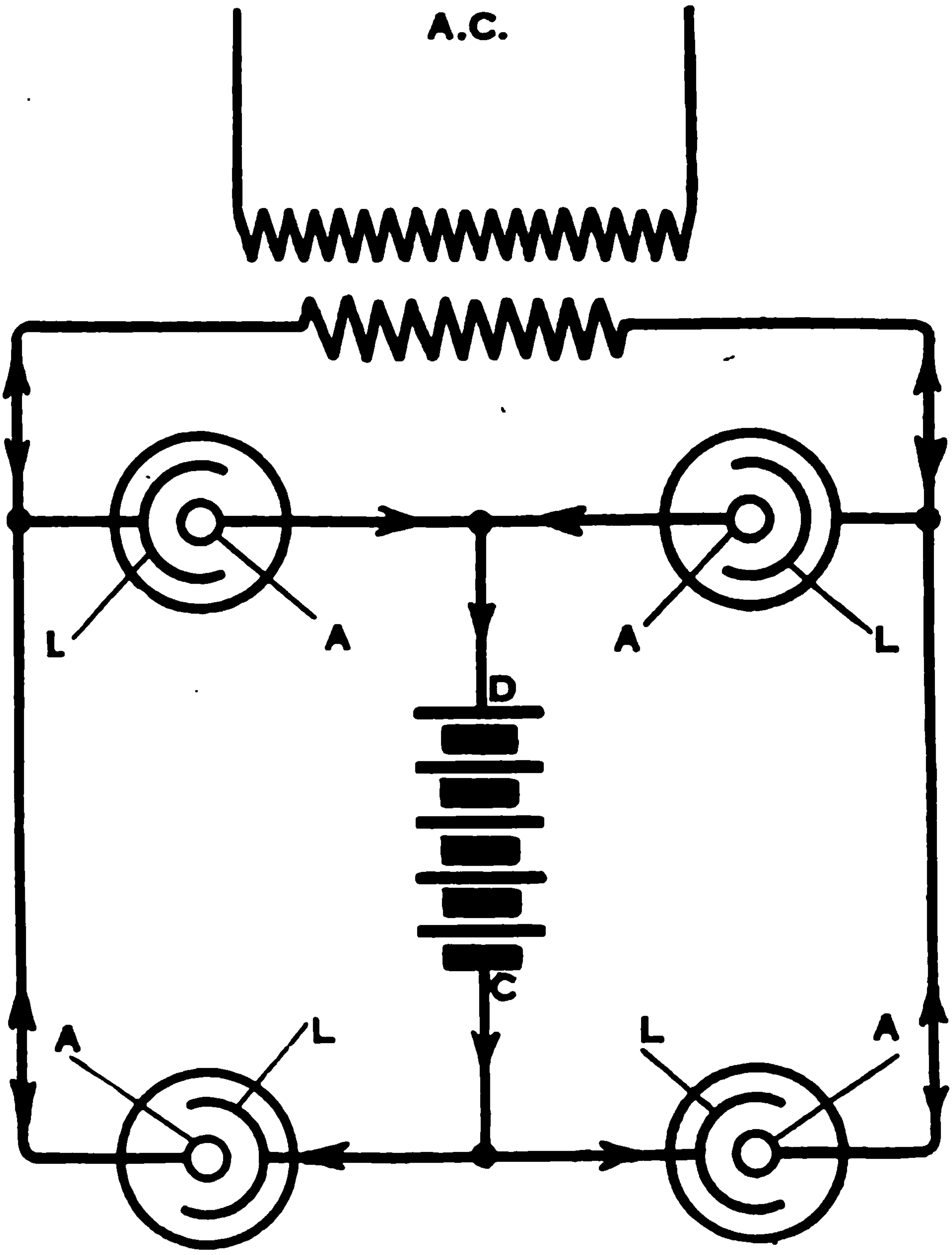


FIG. 953.—Four-cell electrolytic rectifier.

in Fig. 953, both waves of alternating current are utilized in the rectified circuit, and at the same time the full voltage of the A. C. source is obtained. The objection to these rectifiers is that they are very inefficient. The heat generated in the solution means a large loss and the current rectified cannot at most be more than a few amperes. Small currents for charging batteries may be handled with fair success.

The Vibrating Rectifier.—The vibrating rectifier is really an electrically operated vibrating switch. A simple form of this device is shown in Fig. 954. Here the 110-volt alternating source is reduced by means of an auto transformer to about 6 or 9 volts for the purpose of charging a storage battery, *B*. A permanent magnet, *N-S*, has a coil, *M*, surrounding one pole. This coil is connected in shunt with the source. A vibrating armature of soft iron with an adjustable weight, *W*, is attracted by this permanent magnet against the tension of a spring *S*. When a current wave comes over the wire *F* and passes through the coil *M*, the strength of the permanent magnet is supplemented sufficiently to draw the armature down and close the contact *C*, allowing a portion of the current derived from this same wave to flow through the rheostat *R* and the battery *B*, which it charges, and

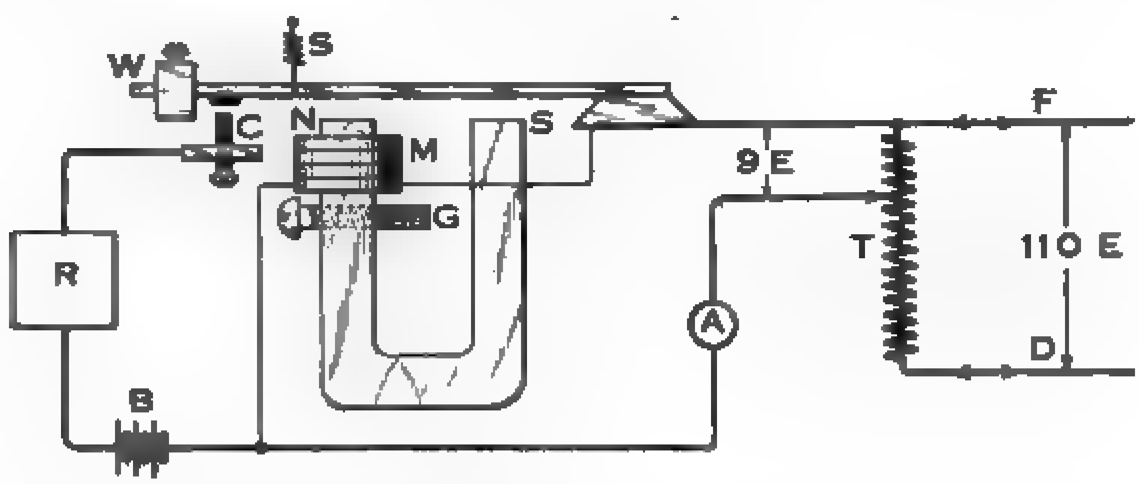


FIG. 954.—Simple form of vibrating rectifier.

back through the ammeter *A* to the auto transformer *T*. When the reverse impulse from the alternating source flows in over the wire *D*, it passes through the coil *M* in the reverse direction to *F*. This opposes the permanent magnetism of *N-S* and diverts the flux from the pole *N*, causing the flux to take the alternate path via an adjustable short-circuiting iron screw *G*. The flux being thus diverted from the pole *N*, the attraction for the armature ceases, and the spring, *S*, raises the armature, breaking the contact at *C*, thus preventing the flow of the reverse impulse through the battery *B*. The same disjointed D. C. current wave shown in Fig. 951 is obtained for the battery.

A more elaborate vibrating rectifier which utilizes both sides of the alternating wave is shown in Fig. 955. Here a pivoted soft iron armature *N-S* has surrounding it a magnetizing coil *R-R* which terminates on the binding screws *P-P'*, to which the stor-

age battery to be charged is connected. Alternating current from the transformer T finds its way over the circuit A, through the magnets M' and M, to the point E. These two magnets are wound so that their lower poles at any instant are both of the same sign. When a storage battery is connected to the termi-

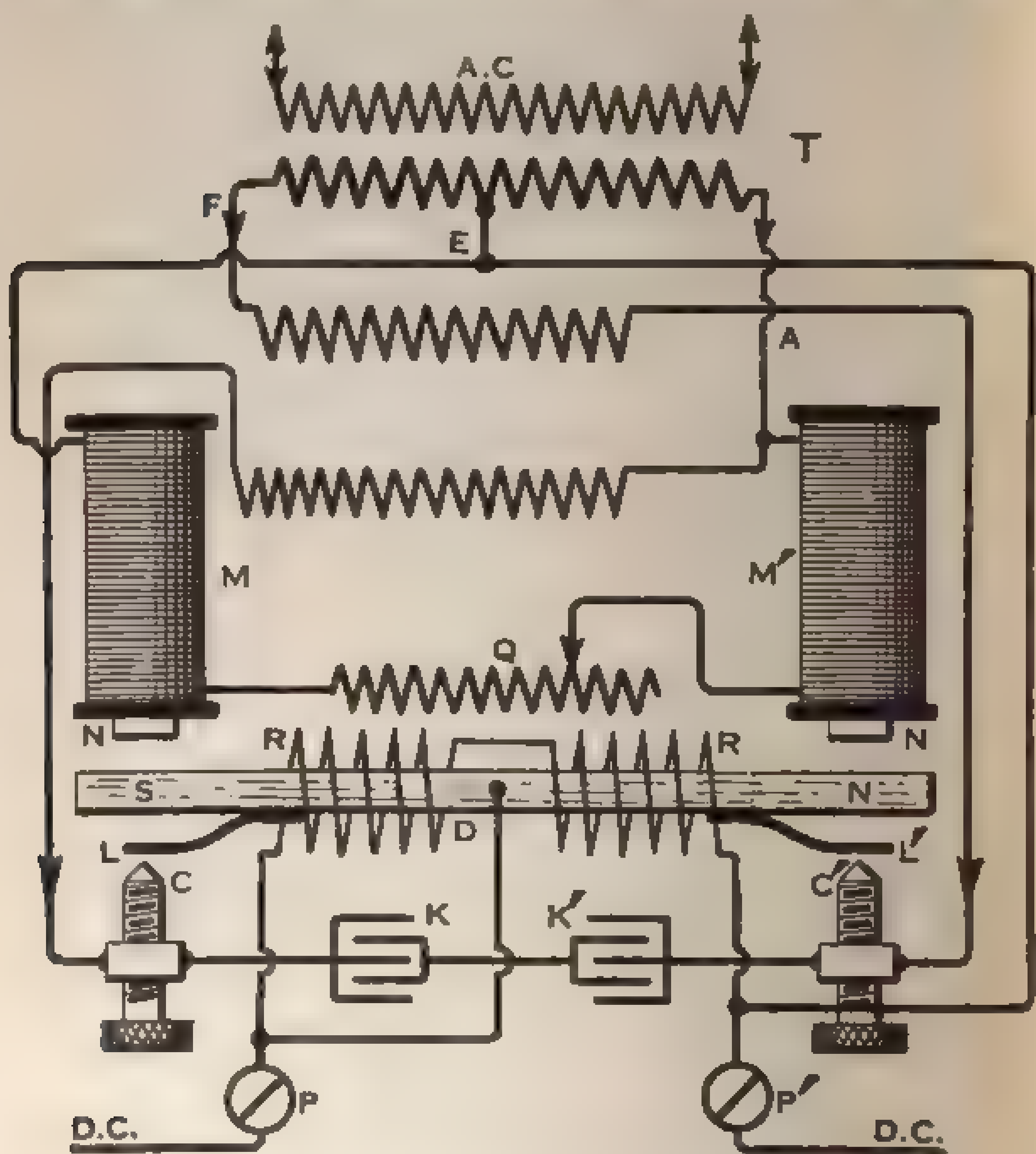


FIG. 955.—Westinghouse vibrating rectifier for charging batteries.

nals P-P' the polarity of the vibrating armature will be determined by the polarity of the battery. Therefore the pole S will attract the pole above it, while the pole N will repel the pole above it. This causes the armature to tilt in such a direction as to close the contact L' on the screw C' and permits current to flow via F-C'-L'-D-P through the battery and back to P', thence to

E. When the current in the transformer reverses, the lower poles of the magnets, *M-M'*, both change to south. This causes the vibrating armature to reverse its position and the contact *L* closes on *C*, thus insuring the flow of current in the proper direction through the battery. It is important to note that it makes no difference in which way the battery is connected to the terminals *P-P'*, as the polarity of the armature is determined by the direction of flow of the current from the battery In fact it is impossible for the charging current to flow through the battery in the wrong direction. The adjusting screws *C-C'* are supposed to be set so that no sparking will occur. This will be insured if the break in the circuit occurs at the exact moment when the maximum height of the A. C. wave corresponds to the counter e.m.f. of the battery. As this varies to some extent the condensers *K-K'* are provided to bridge the contacts. If the wave form from the A. C. source differs much from a sine wave, it may be necessary to alter the adjustment slightly to eliminate sparking. This is because the time of zero current may come a little earlier or later than in the corresponding sine wave. This adjustment is effected by altering the resistance *Q*, in series with the magnets *M-M'*. This serves to shift the phase angle of the resulting flux so as to vary slightly the time at which they reach their maximum strength during each half-wave of alternating current, and accordingly the time at which the contacts break.

The Tungar Rectifier.—The Tungar rectifier somewhat resembles the Fleming valve, the DeForest audion and the Kenatron and Coolidge tubes.

All these devices employ a vacuum tube in which there are two or more electrodes, one of which is maintained hot and the other cold. In such tubes, when an alternating e.m.f. is applied, a current will pass in one direction, but the valve action suppresses the flow of current in the other direction.

Rectifiers for any appreciable currents employing this principle have heretofore been impracticable. The peculiar construction of the Tungar rectifier, however, permits the passage of two amperes when charging three cells of lead battery, while a larger size readily passes 6 amperes and may be used to charge from one to thirty cells. The bulb of the Tungar rectifier contains argon gas at low pressure. This gas is **ionized,** that is, rendered conducting

by the stream of electrons, consisting of small particles of negative electricity which emanate from an incandescent filament within the bulb. A hot electrode will give off this stream of conducting electrons, but a cold electrode will not. It is upon this gas that the current travels from the alternating current source to the storage battery which it is to charge, and the construction is such that the loss in potential within the bulb is only from 5 to 10 volts.

Fig. 956 illustrates the electrical circuits of a small Tungar rectifier capable of passing two amperes and employing one-half of the alternating current wave. The hot filament *D*, which constitutes the cathode, is a closely wound spiral of tungsten wire. The anode, *C*, is a relatively large block of graphite.

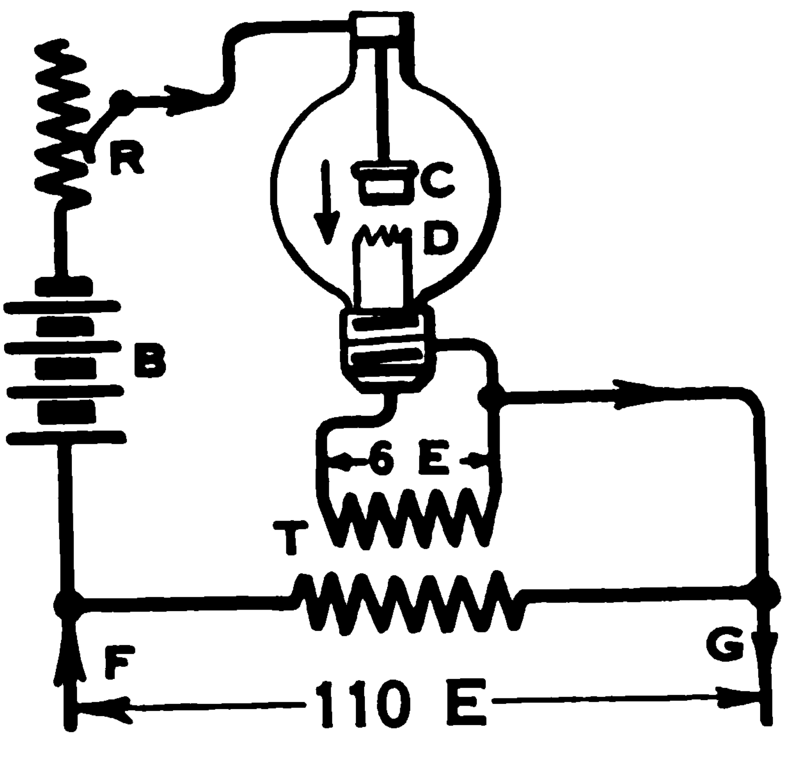


Fig. 956.—Principle of the hot-cathode rectifier.

The principle upon which the rectifying action takes place is as follows: The incandescent tungsten filament is connected to the terminal *G* of the alternating-current source, while the graphite block, *C* is connected to the terminal *F*. As the e.m.f. of the main source alternates it is evident that the filament *D* and the graphite terminal *C* will be alternately positive and negative. Now, when the filament is negative, the cathode stream of electrons emitted from it are drawn toward the anode by the difference of potential across the bulb. These electrons, as they collide with the molecules of argon gas within the bulb, ionize them—that is, they render them conducting in the direction **from** the graphite **anode to** the filament **cathode.** When the e.m.f. applied reverses, the filament becomes positive. No stream of electrons from the graphite cathode will now take place. The gas is therefore not rendered conducting during this half of the cycle, and the valve, so to speak, closes and the flow of current in the reverse direction is shut off.

The bulbs are first highly exhausted and then filled with the purest argon it is possible to obtain. Notwithstanding every

precaution, however, certain impurities find their way into the bulb, and these will eventually cause a disintegration of the cathode. To insure that the argon shall be absolutely free from these impurities, certain chemicals are introduced into the bulb before it is sealed, which will combine with any impurities present and by chemical reaction neutralize their effect. This insures practically pure argon gas within the tube throughout its life. The material employed for purifying the gas usually takes the form of a wire ring surrounding the anode. When the tube is put in service the purifying agent is volatilized and made to absorb any foreign gases present, at the same time causing a deposit on the inside of the globe, which discolors it.

Referring again to Fig. 956, the transformer, *T*, has its primary wound for line voltage, while its secondary is designed for the filament of the rectifier which it is intended to maintain hot. The connections for the storage battery are shown at *B*, with a regulating rheostat *R* in the series with the rectifier across the main alternating-current line *F-G*.

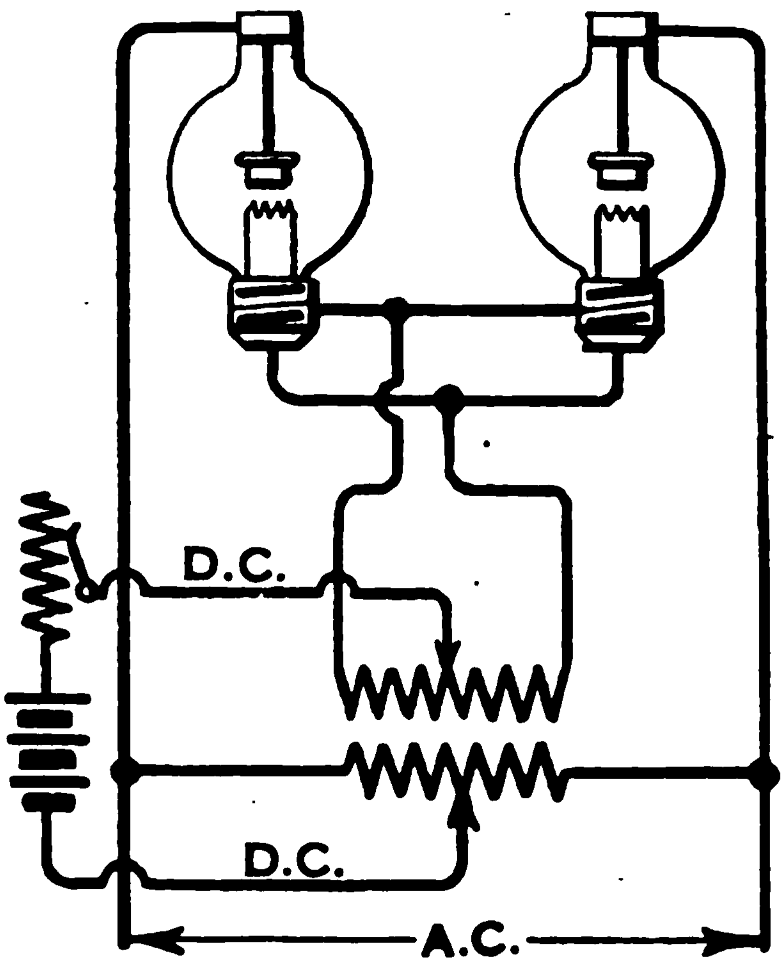


FIG. 957. — Two-bulb hot-cathode rectifier.

Suppose that at a certain instant the side *F* of the source is positive; the current will flow from F in the direction shown by the arrows through the battery, rheostat and rectifying bulb from *C* to *D* and thence back to the opposite side of the alternating-current line *G*. The stream of electrons from the negative filament *D* provides a path for the flow of current from *C* to *D* to charge the battery. Entirely independent of this circuit is the transformer's primary across the source, while the secondary is closed upon the filament which it is to heat. When the e.m.f. of the alternating-current source reverses and the side *G* becomes positive, current cannot flow through the rectifier from *D* to *C* because the cold graphite block *C* does not emit the stream of elec-

trons which is necessary to render the gas conducting in this direction. Thus the current **flows** readily from C to D or **against** the flow of electrons emitted from the hot cathode D, but it **cannot flow** from D to C in the absence of any stream of electrons from the cold graphite cathode.

Fig. 957 shows a rectifier for employing both halves of the alternating current wave and consists of two half-wave rectifying bulbs wired to a storage battery and a transformer. The result is a pulsating unidirectional current. This may be smoothed out to any desired degree by placing a reactance in series on the direct-current side. For storage battery charging it is not necessary, however, to smooth out the wave. The rheostat also may be omitted as the supply voltage, and the delivered current can be regulated from adjustable taps in the transformer.

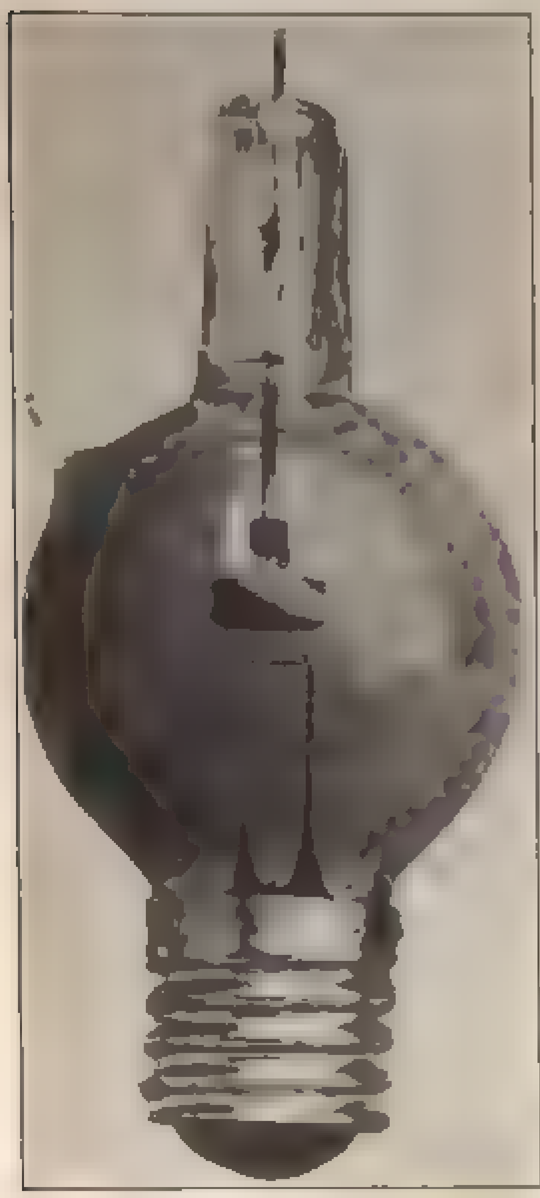


FIG. 958. Tungar hot-cathode rectifier, built by the General Electric Company.

Only small rectifiers up to 500 watts capacity are being used at the present time. The smallest size is a 2-ampere outfit operating at 115 volts, 60 cycles, alternating current. This is capable of charging three cells at the rate of 2 amperes or six cells at 1 ampere or eight cells at 0.75 ampere. The next size is a 6-ampere outfit capable of charging either three or six cells at 6 amperes from a 115-volt, 60-cycle circuit. The third size furnishes 6 amperes and is capable of charging from three to thirty cells at anywhere from 1 to 6 amperes

The efficiency of these rectifiers compares favorably with other devices of similar character. The large size has an efficiency of 75%.

To put the rectifier in operation it is only necessary to connect it to the alternating supply and then connect the secondary circuit to the load, when it will start to operate automatically. If the alternating current should fail, the batteries will not discharge, but the rectifier will immediately resume charging as soon as the alternating-current supply is restored. Its chief field of usefulness is in small capacity work. Fig. 958 is a photographic view of the General Electric Tungar bulb.

The advantages of the Tungar rectifier may be briefly summed up as follows:

1. Low cost.
2. Good efficiency.
3. Inexpensive to install.
4. Adaptable to many uses.
5. Small size and light weight
6. Nothing to adjust.
7. Self-starting.
8. Long life of bulb.
9. Simplicity of operation.

The Westinghouse Company manufactures a similar charging outfit called the **Rectigon.** With two bulbs and an auto transformer, provision is made for charging from three to thirty cells in series. Two circuits are provided, in each of which a charging current of 6 or 7 amperes may be obtained, or the two circuits may be merged into one in multiple giving a charging current of 12 or 14 amperes.

SECTION XVII CHAPTER VII

SYNCHRONOUS CONVERTERS

MISCELLANEOUS TYPES OF RECTIFIERS

1. Explain the principle of the "mercury" rectifier. Sketch connections for a single-phase rectifier.
2. Sketch connections for a three-phase mercury rectifier.
3. What is the efficiency of a mercury rectifier at various voltages? What is the net loss in mercury rectifiers? What is the life of a rectifier bulb?
4. Explain the "electrolytic" rectifier. Sketch.
5. Sketch an electrolytic rectifier of one, two and four cells. What is the character of currents obtained? What are the relative voltages in each case? Where should each arrangement be used?
6. What are the advantages and disadvantages of an electrolytic rectifier?
7. Explain the principle and construction of a vibrating rectifier. Sketch.
8. Explain the principle and construction of the "Tungar" and "Rectigon" rectifiers.

SECTION XVIII CHAPTER I

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

REQUIREMENTS OF GAS-ENGINE IGNITION

Internal-combustion engines may have the explosive mixture in the cylinder fired in a number of different ways, but at the present time all internal-combustion engines used for automobile, tractor, and airplane propulsion depend upon some form of electrical ignition for igniting the fuel charge in the engine cylinder, and this is accomplished by producing a spark within the combustion chamber as the piston nears the end of the compression stroke.

Internal-combustion engines used for automobile, tractor and airplanes are of the four-stroke-cycle type. They require four separate strokes of the piston to complete one engine cycle, namely, the suction stroke in which a charge of air and fuel is drawn into the cylinder; the compression stroke in which the vaporized fuel is compressed by the piston into the upper part of the cylinder, or combustion chamber; the power stroke, at the beginning of which the gaseous mixture is ignited, and during which the engine is delivering useful power; and the exhaust stroke, during which the burned gases are expelled from the cylinder. To complete these four strokes of the piston, or one complete engine cycle, requires two revolutions of the crankshaft; therefore in any four-cycle engine each cylinder will have one working stroke for every two revolutions of the crank shaft, and therefore a spark is required in each cylinder for every two revolutions of the crank shaft. Many of the modern six, eight, and twelve-cylinder high-speed engines have a maximum working speed of about 3,000 r.p.m. which requires about 300 sparks per second, and from this may be seen the importance of providing an accurate and dependable ignition system which will supply each cylinder with a good spark at just the proper time.

Another type of internal-combustion engine which has a limited use for motor boats and farm lighting plants is known as the two-stroke-cycle type of engine and requires but two strokes of the piston or one revolution of the crank shaft to

complete one engine cycle. The usual suction and exhaust strokes are absent in this type of engine, the mixture being compressed in the crank case or by an external pump and forced into the engine cylinder through a port uncovered by the travel of the piston, at the same time displacing the burned gases which are expelled through a separate port near the bottom of the cylinder also opened by the travel of the piston. For this type of engine a spark is required for each revolution of the crank shaft as the cycle is completed in this time, but due to mechanical construction the speed of a two-cycle engine is

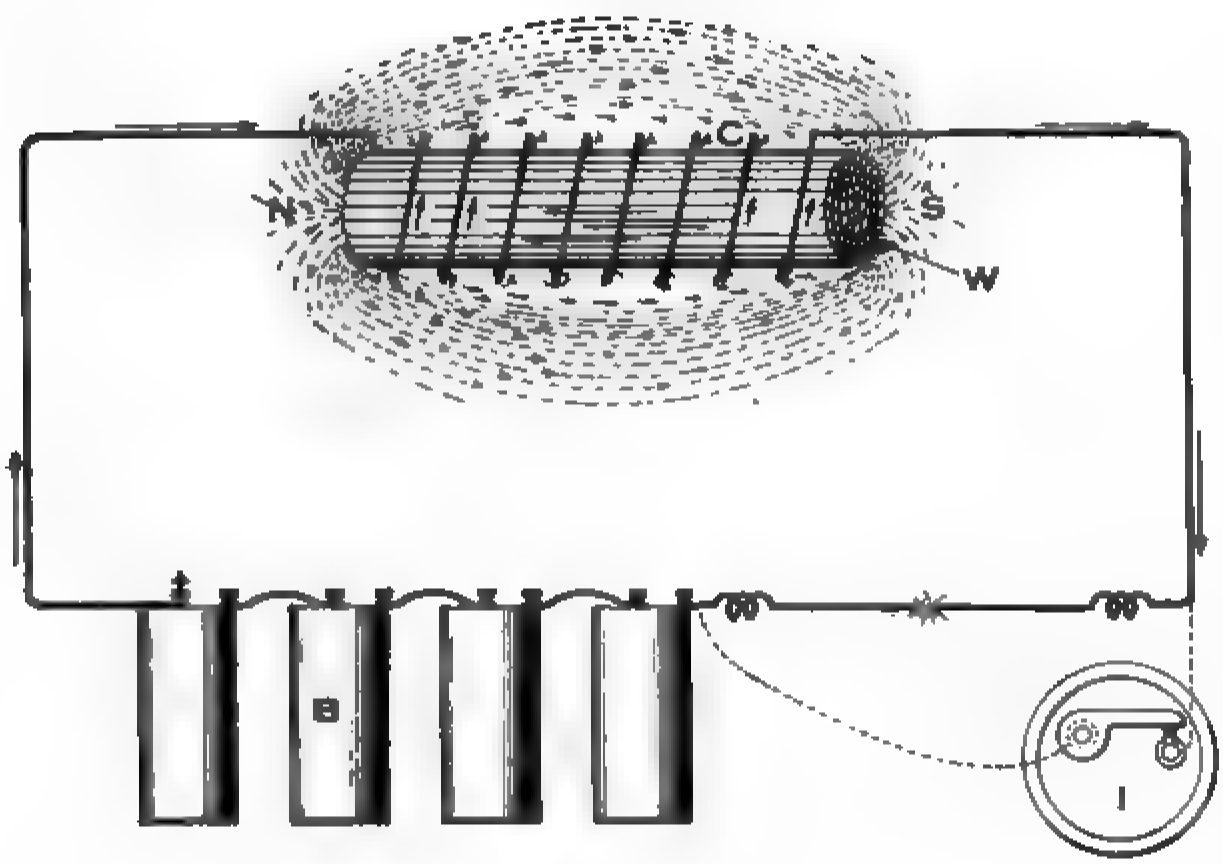


FIG. 959.—Principle of make-and-break system of ignition.

limited to about 1,000 r.p.m.; therefore the total number of sparks required of the ignition system never reaches the maximum required for the four-cycle type.

Make and Break Ignition

Electrical ignition may be accomplished by either the make-and-break system or by the jump-spark system. At the present time, however, the former is being used only on some slow-speed farm and marine engines and also on engines having a very high compression.

In the make-and-break system of ignition, Fig. 959, the current is made and broken by an igniter *I*, the contacts of which

extend into the combustion chamber. The igniter is operated by a cam and push rod mechanism traveling at one-half engine speed in the four-stroke-cycle type, and so timed that a spark is produced in the cylinder as the piston nears the head-end dead-center. The spark occurs at the instant that the contacts open and is due to the sudden stoppage of the current in connection with the low-tension spark coil. The coil itself consists of a single winding, *C*, over a soft iron core made up of a bundle of annealed iron wires, *W*. If the current through the coil is suddenly interrupted by opening the circuit, a spark of considerable intensity will occur at the point of interruption. This spark occurs between the points of the igniter within the cylinder and fires the fuel charge. The spark is caused by the voltage and current induced due to the cutting of each convolution of the coil by the magnetic flux surrounding it while the current is flowing, but which collapses the instant that the circuit is broken. This induced voltage may reach a momentary value of several hundred volts and is sufficient to break down the resistance of the air gap between the igniter contacts when they are opened, thus allowing the induced current to flow across the gap and produce a very hot spark in the cylinder.

Jump-Spark Ignition

In the jump-spark system of ignition, low-voltage current from a 6 to 12-volt battery or magneto is passed through an induction coil which transforms it into a high-voltage current having a pressure of several thousand volts. This high-voltage current is then made to jump the points of a spark plug inside of the cylinder and ignites the explosive mixture.

Induction coils used for ignition purposes may be either of the vibrating or non-vibrating type. The vibrating type operates with a **timer** and gives a shower of sparks at the plug, while the non-vibrating type operates with a **breaker** mechanism and gives a single spark at the plug. The non-vibrating coil is the most popular for automobile ignition, and its application to the jump-spark ignition system is shown in Fig. 960. The coil consists essentially of a primary *P*, and secondary winding *S*, both wound on the same core, which is made up of a bundle of soft iron wires. The iron for the core is made as soft as possible so that it may be magnetized and demagnetized very rapidly.

The primary winding consists of several layers of about No. 18 B. & S. gauge cotton or enamel insulated wire, wound over the core and forming an electro-magnet. The secondary or high-tension winding to which the spark plug is connected is wound over the primary and consists of several thousand turns of about No. 36 B. &. S. gauge silk or enamel insulated wire. The windings are sometimes made up of layers running the entire length of the coil, and sometimes made up in pancakes or sections and then assembled over the primary, and connected so that their windings will be in series. Each layer and section is insulated

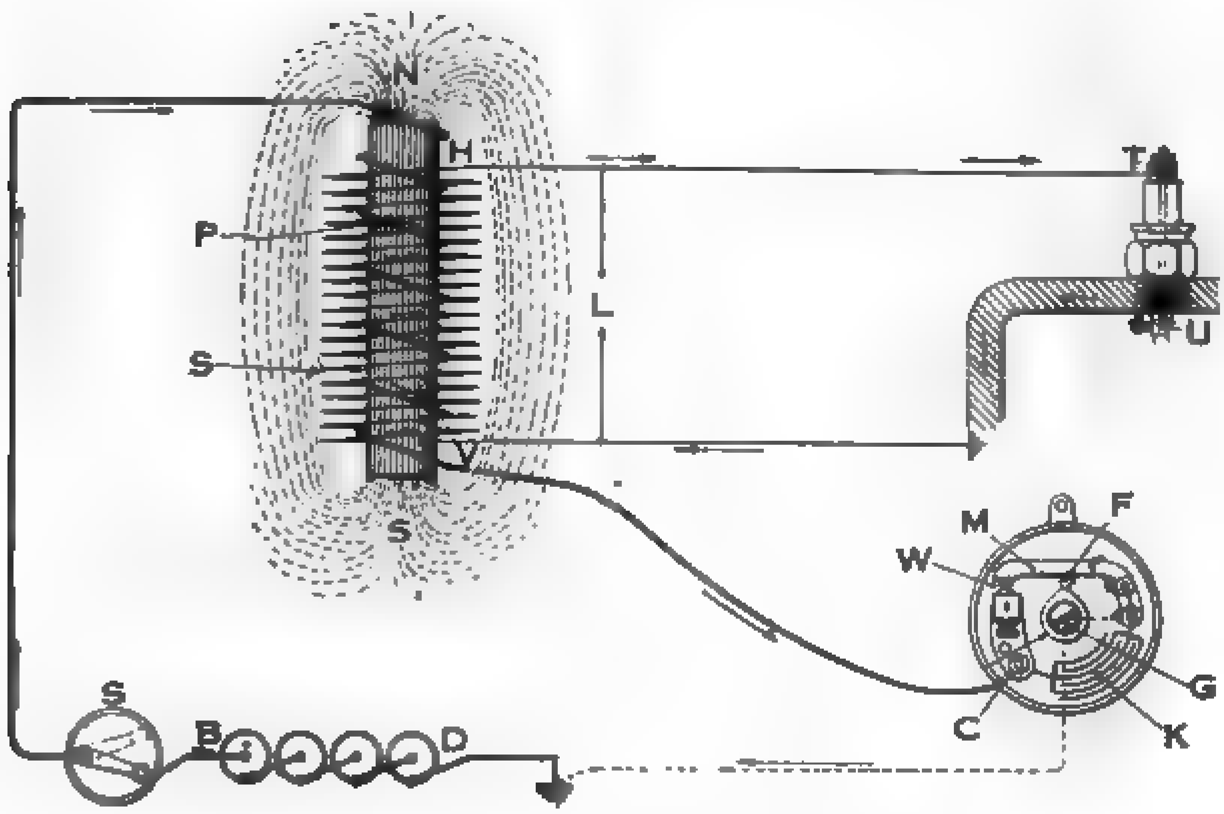


FIG. 960.—Principle of jump-spark ignition.

with waxed paper, and after completion the whole coil is impregnated with wax so as to prevent as far as possible any possibility of a breakdown of the insulation between the layers. The actual pressure necessary to jump the points of the spark plug under normal compression is about 5,000 or 6,000 volts with the points properly adjusted, but the secondary is sometimes subjected to a strain of 10,000 to 20,000 volts, and hence every precaution must be taken to prevent the escape of the current at some point other than the plug. If the insulation of the coil should break down, the current would flow from one layer to another, thus forming an arc within the coil rather than at the plug.

The perfection of light alloys for pistons for automobile en-

gines and better balancing of rotating parts has led to the development of high-speed, high-compression engines.

The **open-circuit** battery systems of ignition apparently do not meet the present requirements and practically all modern systems employ **closed-circuit** ignition.

The term "closed-circuit," as applied to battery ignition systems, may be understood from an inspection of the breaker cams in general use. Invariably these breaker cams have lobes of such a shape that the period during which the breaker contacts are kept apart is considerably less than the length of time during which they are kept closed, and hence permit the primary current to flow.

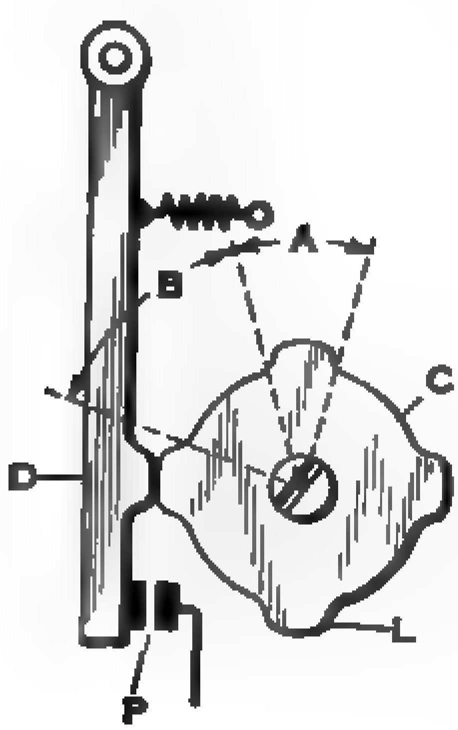


Fig. 961—Cam-operated make-and-break device.

Referring to Fig. 961, a four-lobed breaker cam is shown that may be considered typical of those in general use, so far as relative values of angles *A* and *B* are concerned, which represent relative values of the time interval during which the primary circuit is open, and during which it is closed, respectively. A condenser, of course, is necessary to prevent pitting of the contacts, as in open-circuit systems. When dry, primary batteries were used for ignition, economy of battery current was of great importance, as the life of the battery was prolonged as the angle *B*, during which the circuit was closed, was decreased.

The economy of battery current is not now so important, as storage batteries are generally used for lights and starting, and it is more desirable to get good ignition, especially at high engine speeds, hence more current is needed and the current must flow for a longer time to produce complete magnetic saturation of the core. Prolonging the period during which the circuit is closed produces the higher degree of magnetic saturation sought.

The use of comparatively large primary currents in the modern battery system necessitates some protective device to prevent burning out of the primary winding of the induction coil and complete discharge of the battery, should the ignition switch be allowed to remain closed with the engine not running and the

breaker contacts closed. Occasionally the contacts stick or weld. Most systems use a coil of special wire in series with the primary circuit, which limits the current to a safe value, as the resistance of this wire rises rapidly as it heats. This wire is mounted externally on a porcelain form and in such a manner as to radiate its heat readily. Another method, used in the Connecticut system, is a thermostat in series with the primary circuit which operates a vibrator and mechanically opens the ignition switch in case it has been left in the *on* position when the engine is not operating.

In Fig. 960 is shown the circuit diagram of a simple jump-spark ignition system for a single-cylinder, four-cycle engine using a non-vibrating coil operating with a breaker for opening and closing the primary circuit. The contacts *W* of the breaker are normally held closed by a spring and are opened only when the lobe of the cam strikes the movable breaker arm. The cam is geared so as to turn at cam-shaft or one-half crank-shaft speed, so that a spark will be produced every two revolutions of the engine, or once in every cycle. The cam must be so timed in its operation, with respect to the moving piston, that the breaker points will be opened and the spark produced at the plug at the proper instant for firing, which will occur as the piston is nearing the end of the compression stroke.

Assuming the cam to be in such a position that the breaker points are closed, the path of the primary current when the switch is closed is from the positive terminal *B*, of the battery, through switch *S* and primary winding *P* of the coil, magnetizing it, as shown, and to the insulated point *C* of the breaker. It then passes through the contacts and contact arm *M* to ground *G*, returning through ground to the negative terminal *D* of the battery, which is also grounded. When the primary circuit is opened by the lobe of the cam raising the breaker arm and separating the contacts, the core is very rapidly demagnetized. As the magnetic lines of force collapse, they cut the primary and secondary windings and induce a voltage in each in such a direction as to cause a current to flow in the same direction as the original battery current. By having many turns in the secondary winding a voltage sufficiently high will be induced in the secondary circuit to jump across the spark-plug gap, thus completing the circuit and giving the desired spark in the engine cylinder. The path of the secondary high-tension current is

from one end of the secondary winding *H* to the spark-plug, *T*, through insulated terminal, jumping the air gap in the cylinder between the plug points *U* to the engine frame and returning through the frame and grounded circuit to the other end of the secondary winding *V*.

From this it will be seen that the primary current is utilized only for magnetizing the core of the induction coil while the induced secondary current is used to produce the spark in the cylinder. When the breaker contacts are closed and the core magnetized by the primary current, a voltage is induced in the secondary as well as when the core is demagnetized, but owing to the fact that the core is magnetized much more slowly than it is demagnetized, the voltage induced in the secondary is not sufficiently high to jump the gap.

The primary circuit of the jump-spark ignition system is very similar to the make-and-break ignition system, and the same kind of spark which was produced at the points of the igniter will be produced at the breaker contacts when they are opened; but in the latter case this is objectionable as it would cause burning of the contacts and prevent the core of the induction coil from being demagnetized rapidly enough to induce the necessary high voltage in the secondary circuit. This burning of the contact is prevented and the action of the coil greatly improved by connecting a condenser, *K*, across the breaker contacts.

Condensers for ignition purposes are usually made up of alternate strips or layers of tin foil and paraffined paper or thin sheets of mica. The condenser should be located as near the breaker contacts as possible and is usually located in the breaker housing or in the coil assembly where it will be protected from the moisture and heat of the engine.

Referring to Fig. 962, the action of the condenser is as follows: When the breaker contacts open, thereby interrupting the primary current, a voltage is induced in the primary circuit which is in the same direction as the original battery current, and which would otherwise cause arcing across the breaker contacts. This voltage, however, now causes a surge of current to pass into the condenser *K* and charges it. The reaction of this charge amounts to a condenser discharge which takes place instantly in the opposite direction back through the primary

circuit, thus tending to send a current through the primary winding of the coil in the opposite direction and helping to very quickly reduce the magnetism of the coil to zero, and thus assisting to induce a very high voltage in the secondary winding.

The exact size or capacity of the condenser must be determined by experiment for each individual system, depending upon the amount and size of wire in the primary circuit, the size and permeability of the core, and the speed of the breaker contacts. It is important that the condenser be well insulated, as it is subjected to the full inductive kick of several hundred volts from the primary winding, and a defective condenser will be apparent by sparking at the breaker contacts and a very poor spark at the plug. It has been estimated that a good condenser of the proper capacity will intensify the spark at the plug from 20 to 30 times, and many systems refuse to operate at all if the condenser should be broken down.

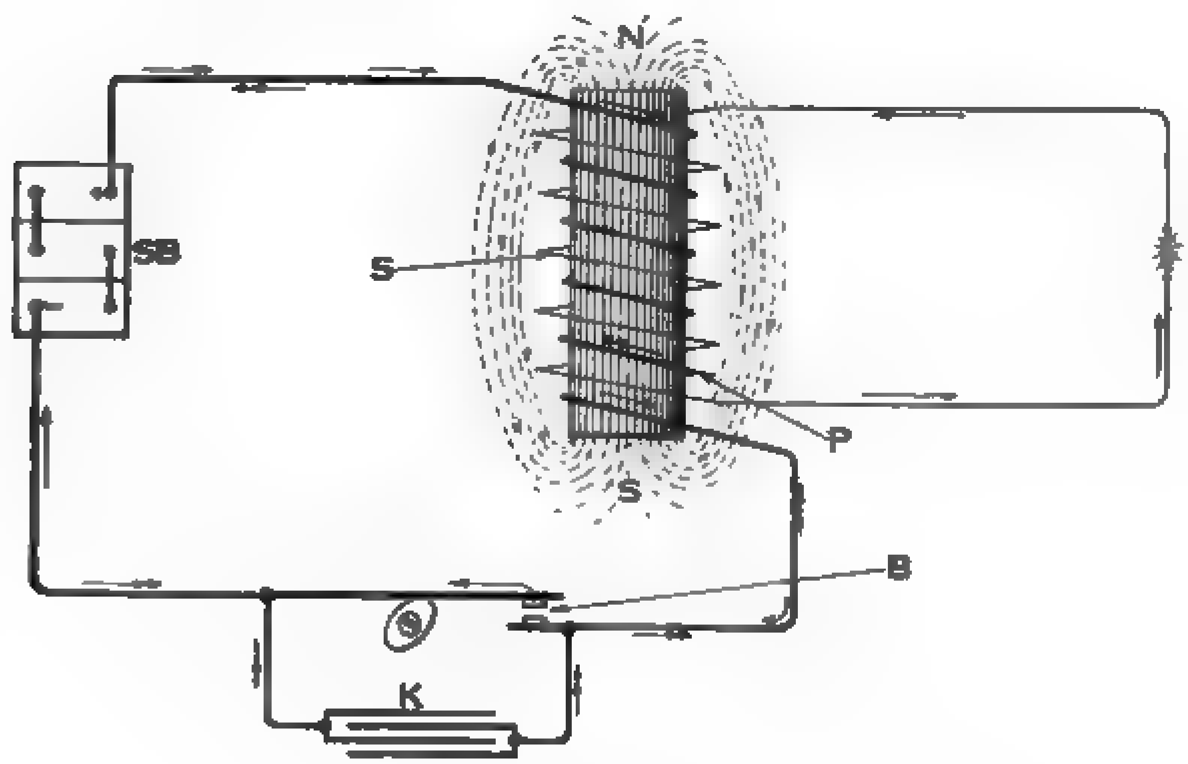


FIG. 962.—Induction coil circuits showing location of condenser to increase the secondary spark.

Many coils have incorporated in them a safety gap which is adjusted so that the distance between the points is from 5/16 inch to 3/8 inch and connected in parallel with the spark plug as shown at *L*, in Fig. 960. The purpose of the safety gap is to provide a by-path for the high-tension current in case the spark-plug leads should be disconnected or the spark-plug points become so widely separated that the current will not pass between

them under high compression of gas in the cylinder In case any break should occur in the secondary circuit which would offer a higher resistance to the secondary current than the path across the safety gap, the discharge would take place between the points of the safety gap and prevent the secondary winding of the coil from being subjected to an excessive pressure which

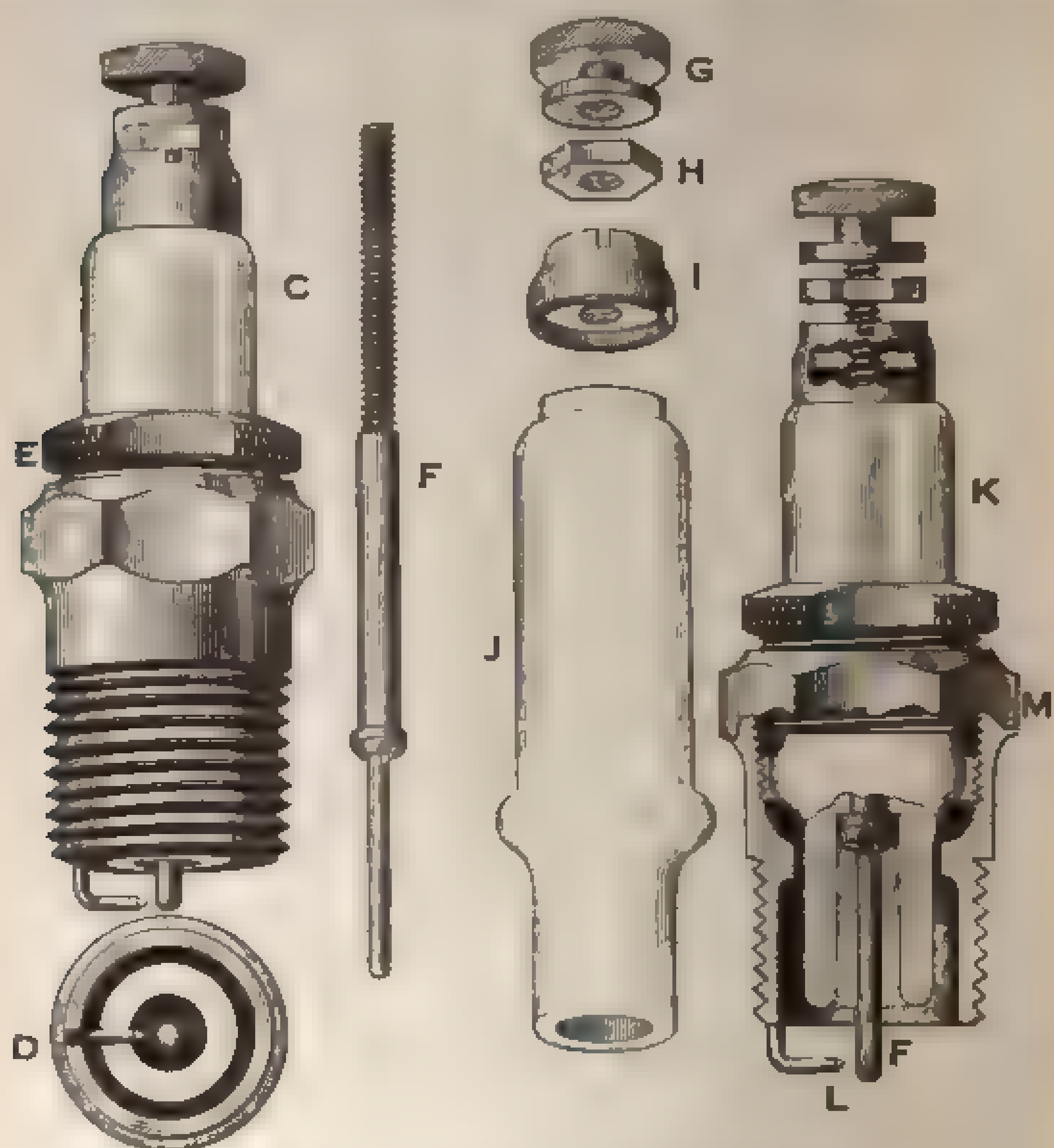


Fig. 963.—Various parts of the standard spark plug.

might break down the insulation of the coil and cause short circuits between the turns.

Spark Plugs

Spark plugs are used for leading the high-tension current into the combustion chamber, and the interior construction of a typical plug is shown in Fig. 963. The central terminal *F* is insulated from the outer shell *M* and terminal by a porcelain or

mica cylinder *J*. The outer shell screws into the head of the engine cylinder so that the points project into the combustion chamber, and is therefore grounded. The gap between the points is adjusted to about 0.03 inch for engines of normal compression, although the proper adjustment of the gap will vary slightly with the compression pressure and the type of ignition equipment used. Some plugs have several grounded terminals, in which case the gaps should all be set alike. After considerable use the terminal points burn and the gap widens. It should, therefore, be adjusted from time to time. In case a multiple point plug is used it is claimed that the points will not be burned away as rapidly and therefore will have to be adjusted less frequently.

The requirements of a good serviceable plug are:

1. The insulation, whether of porcelain or mica, must not be readily coated by a deposit of carbon, which is largely due to too rich a mixture or too much lubricating oil. The electrical resistance of the gas in the cylinder increases as compression takes place, and a weak battery which may be able to produce a spark across the points in air may utterly fail to produce a spark in the cylinder where the gas is under pressure. A similar result will occur if the porcelain insulation of the plug is cracked or badly coated with carbon. The plug may spark perfectly in the open air and yet sufficient leakage occur to short-circuit the terminal points through a crack in the insulation when placed in the cylinder. The length of the path from the insulated high-tension terminal to the grounded terminal over the surface of the porcelain or mica insulation should be made as long as possible to reduce the leakage from the deposit of carbon which gradually accumulates over the plug.

2. The plug should be so constructed that it may be readily taken apart, easily cleaned, assembled again, and made gas tight without danger of destroying the insulation.

Spark plugs may be provided with either a one-half inch tapered pipe thread, or the threaded part may be made seven-eighths inch in diameter straight, with 18 threads per inch. The latter has been adopted as standard by the S. A. E. and is used on nearly all American made cars. The tighter the tapered plug is screwed into the cylinder the tighter the fit, and this fit is relied upon to prevent any leakage of gas around the plug. Plugs

having a straight shank require a copper gasket against which the plug must be tightly seated to insure that no gas will leak around the plug. The terminal points of the plug between which the spark takes place should be made of non-oxidizable metal and be capable of standing high temperatures.

The successful operation of the plug is determined very largely by its proper installation in the cylinder and is influenced by the type of cylinder head used and the shape of the combustion chamber. On account of the variation in thickness of the cylinder heads on different types of motors, spark-plug shells are made in several different lengths so that the sparking points may always be properly located in relation to the gases in the combustion chamber. The length of the shell should be such that when the plug is screwed in the cylinder the inner edge of the shell will be flush with the inside of the cylinder wall as

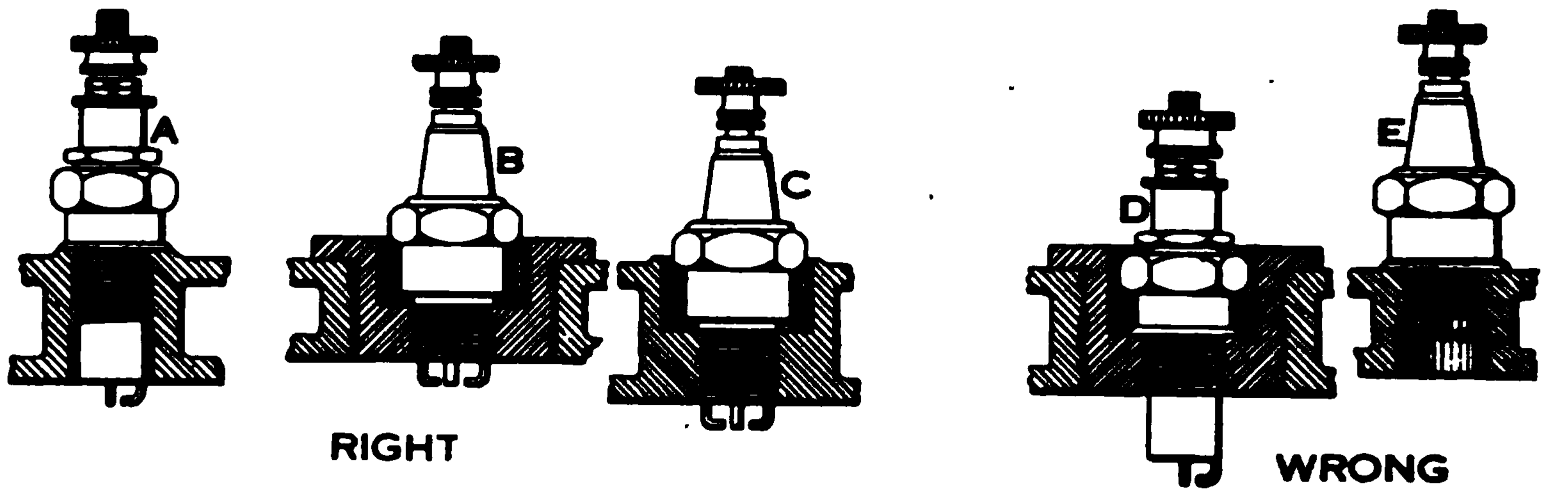


FIG. 964.—Right and wrong types of spark plugs to use in various cases.

shown at *A*, *B*, *C* in Fig. 964. If the shell extends beyond the inner surface of the cylinder as at *D*, there is danger of the plug overheating, and probably causing premature ignition, or the porcelain insulation may become cracked from the high temperature. If the plug does not extend entirely through the cylinder wall, as at *E*, a pocket is formed in which the burned gases collect and there is danger of misfiring, owing to the fact that the sparking points are surrounded with burned gases instead of fresh gases. There is also danger of the plug becoming fouled by oil and carbon accumulation which would result in short-circuiting.

SECTION XVIII CHAPTER I

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

REQUIREMENTS OF GAS ENGINE IGNITION

1. Explain the principle of the four-stroke cycle gas engine.
2. Explain the principle of the two-stroke cycle gas engine.
3. Explain the general plan of "make and break" ignition for automobile gas engines.
4. Explain the general plan of "jump spark" ignition for automobile gas engines.
5. Explain the scheme of the "open-circuit" contact breaker and "closed-circuit" contact breaker. Where is each type used and what are its advantages?
6. Explain the construction of the condenser employed in ignition work and just how it operates to improve the quality of the spark.
7. Explain the object of a spark plug and the construction of a standard type.
8. Why should a spark plug be of a certain length and what are the disadvantages of having a plug either too long or too short.

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

MODERN BATTERY IGNITION

Induction Coils.—In the **vibrating** type of induction coil a **vibrator** is employed for producing a series of **interruptions**, and a **timer** is used for the initial closing of the **circuit**. In the **non-**

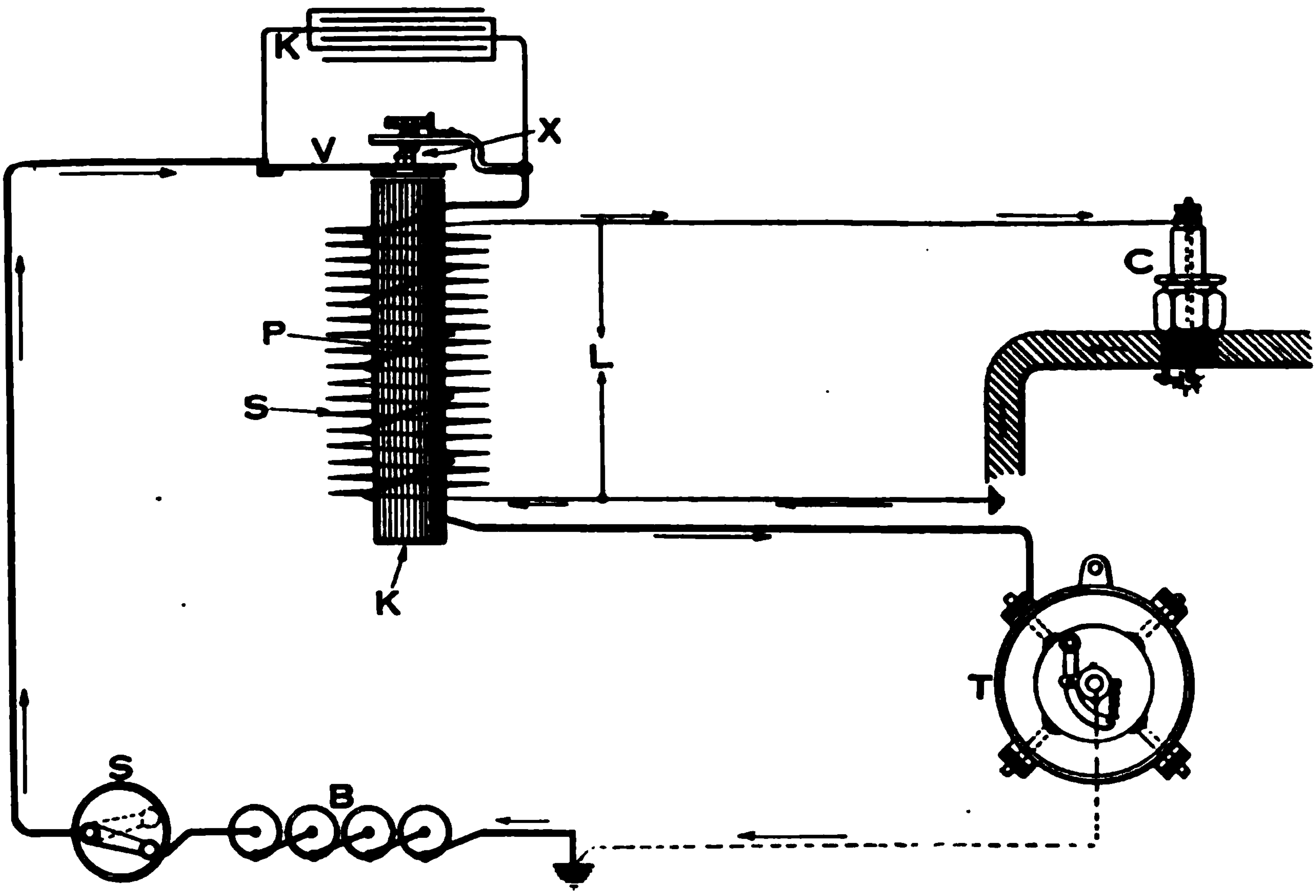


FIG. 965.—Circuits for vibrating coil and timer.

vibrating type of coil the vibrator is omitted **entirely**, and a **breaker** is used for opening and closing the **primary circuit**. In the vibrating type a core consisting of a **bundle of soft iron wire** is employed, over which the primary **winding of heavy, insulated** wire is wound. Over this is a secondary **winding of fine, insulated** wire. A vibrator is mounted on the coil housing **and connected in** series with the primary. A condenser is **connected across** the vibrator contacts to prevent arcing and to **increase the secondary** voltage. Fig. 965 illustrates the circuits for a **vibrating coil and** timer, in the jump-spark system of ignition. **There** are **two**

distinct circuits, one the primary and the other the secondary, as with the single spark system which omits the vibrator. The primary circuit includes the battery *B*, switch *S*, vibrator *V*, timer *T*, and condenser *K*. The secondary circuit includes the spark plug *C*, and the secondary winding *S*, of induction coil only. The timer, driven by the cam-shaft of the engine, closes the circuit periodically. The current then flows from the battery through the primary circuit, as shown by the arrows. The core of the induction coil is magnetized and exerts

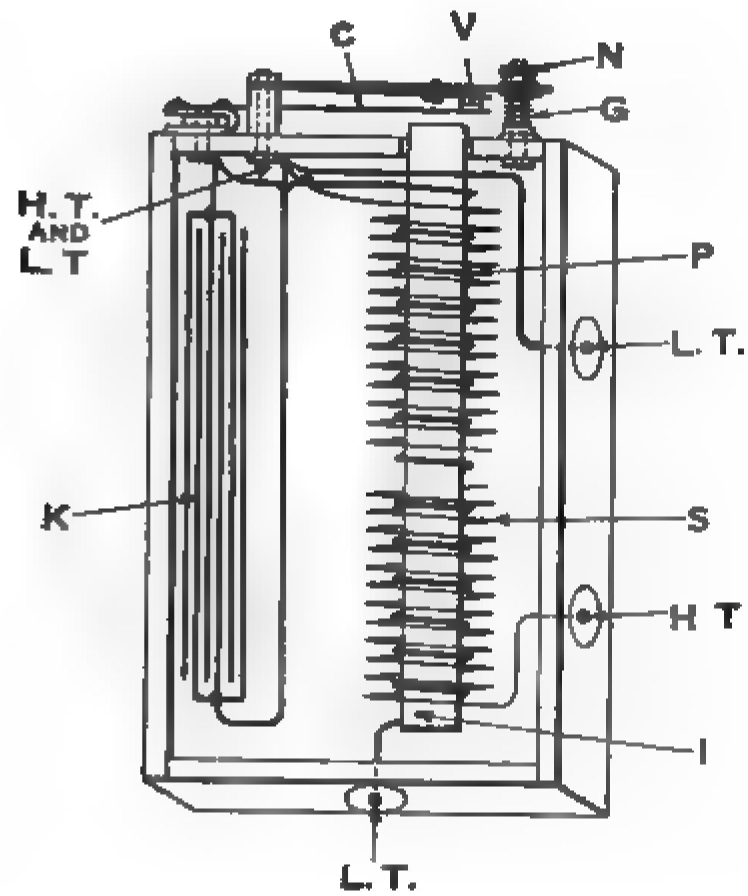


Fig. 966.—General arrangement of parts for vibrating induction coil including condenser.

an attraction for the armature of the vibrator which causes a separation of the contact points. This interrupts the primary circuit, and the current ceases to flow. The iron core immediately loses its magnetism, and the spring returns the vibrator contacts to the closed position. This is repeated very rapidly, and the vibrator will continue to vibrate so long as the roller makes contact with one of the segments in the timer. Whenever the vibrator contacts open, the current in the primary and the magnetic flux in the core very quickly cease. This induces a

high-voltage current in the secondary which produces a spark at the plug. The e m.f. of self-induction which tends to produce sparking at the vibrator contacts is absorbed by the condenser, and a shower of sparks corresponding in number to the vibrations of the vibrator is produced at the spark plug. These sparks continue throughout the time during which the roller is in contact with the metallic segment of the timer.

While the high-tension and low-tension circuits of an induction coil may be kept entirely separate, there is no advantage in isolating them from each other. It is quite common to connect the windings together at one point so that ignition-induction coils

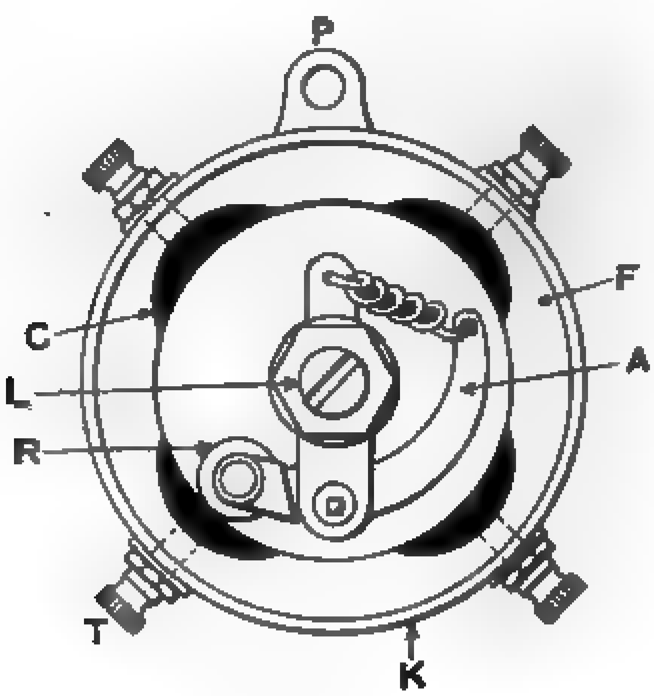


Fig. 967.—Contact-making timer for primary circuit.

are frequently found with three terminals instead of four. One of these terminals is one end of the low-tension winding, another is one end of the high-tension winding, while the third is common to both high-tension and low-tension windings. Fig. 966 shows the arrangement of such a coil designed for a Ford car. It is customary to employ a separate coil for each cylinder on an automobile where vibrating coils are used. These coils are generally placed in a box on the dash and are arranged with sliding spring connections shown at A, C, and D, Fig. 968, so that they may be removed individually without disturbing the car wiring. The switch S on the front of the box controls the ad-

mission of current from either battery B or magneto M to the coils The timer shown at *T* in Fig 965 is a revolving switch designed for completing the circuit in the battery or magneto line

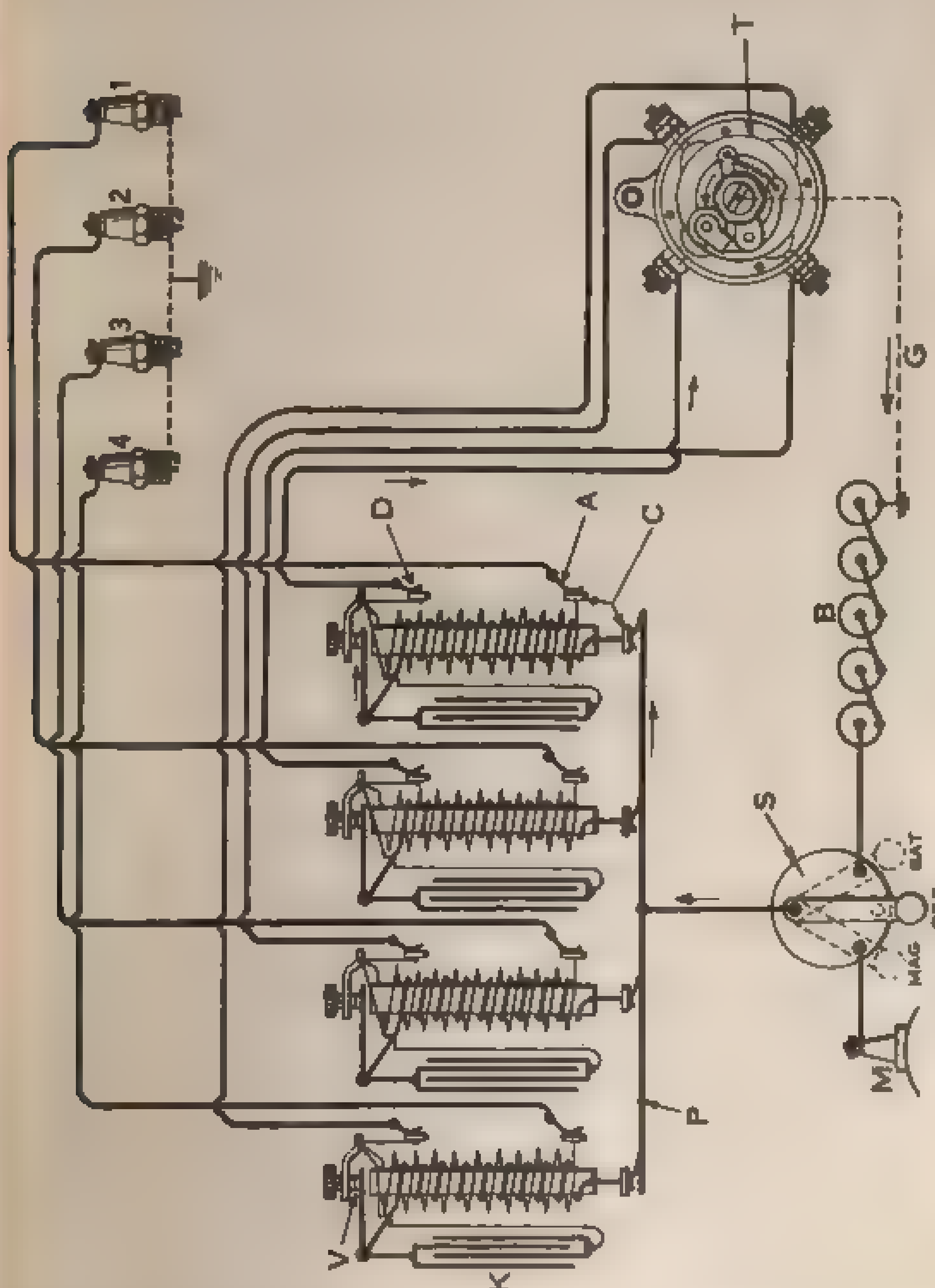


Fig. 968. Standard wiring diagram showing actual connections for Ford ignition system.

at the proper moment to energize the induction coil which supplies the spark for firing a certain cylinder.

Fig. 967 shows the general appearance of the timer used on a Ford car. The roller mechanism *R* is mounted on the end of the camshaft *L* and therefore revolves at camshaft speed.

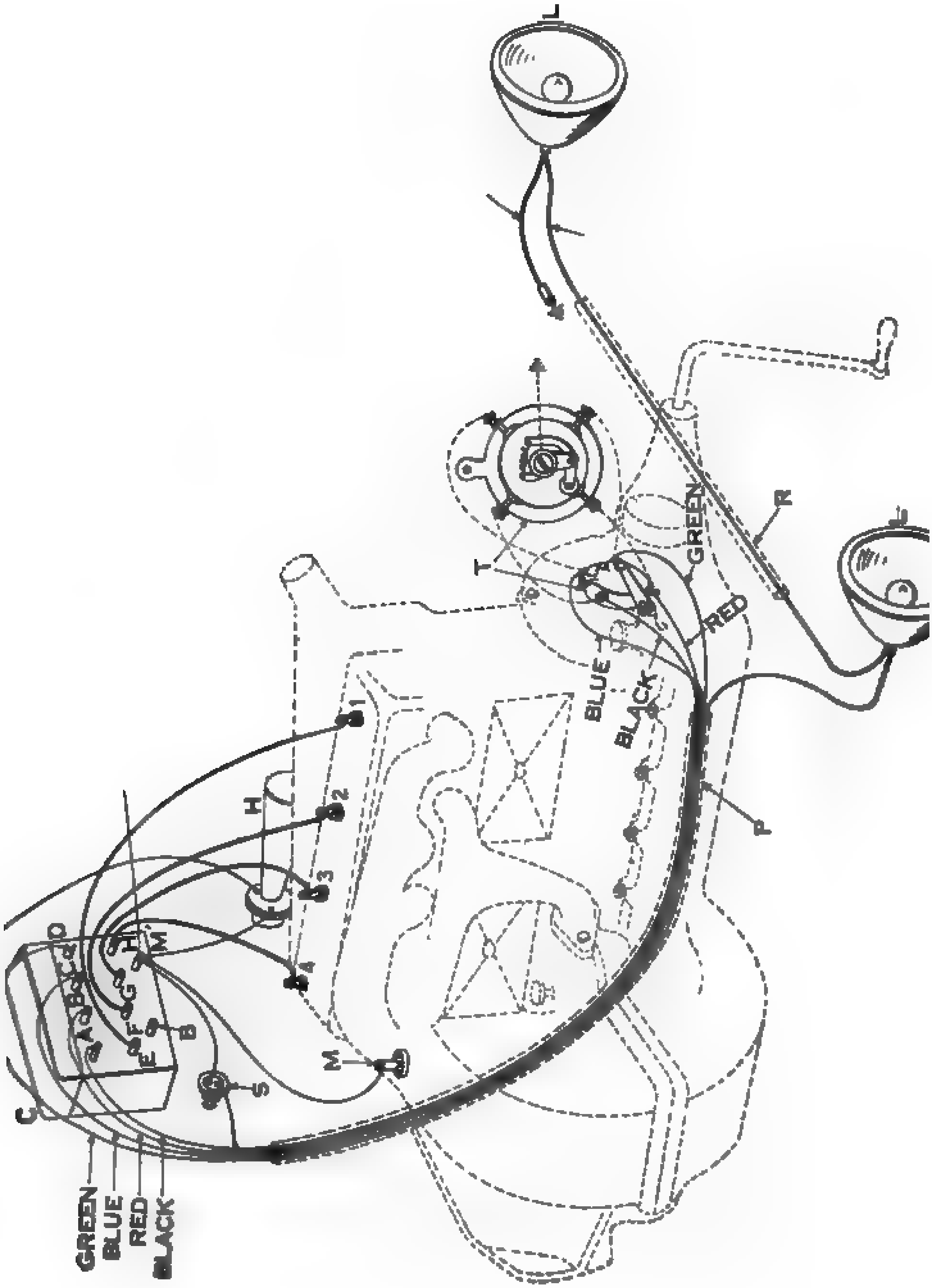
As the roller touches each of the four metallic insulated segments in turn, a circuit is completed from the magneto or battery through the primary of the induction coil and through the particular segment which the roller touches and induction coil connected thereto. This causes the vibrator to operate, and a shower of sparks in rapid succession is produced at the plug supplied by this coil. The surrounding framework of the timer does not rotate, but it is capable of being shifted forward or backward through a limited angle so as to alter the time in the engine cycle when the firing shall occur.

Fig. 968 represents the electrical circuits through the four induction coils, timer, battery, and switch on a Ford car. The spring contacts by which each of the induction coils completes its circuits when placed in the retaining box are shown at *A*, *C*, and *D*. The plate in the bottom of the box which is common to all the coils, and leads to the switch, is shown at *P*, the condensers at *K* and the vibrators at *V*.

Fig. 969 shows the actual position of the induction coils with the low-tension terminals *A*, *B*, *C*, *D*, and the high-tension terminals *E*, *F*, *G*, *H*, the battery terminal *B*, magneto terminal *M*, wiring, timer and headlights.

Time of Firing

On all automobile engines it is necessary to vary the time of firing when the speed of the engine varies, as there is a certain time interval after the spark is produced before the explosion takes place and this interval is independent of the speed of the engine. If the engine is operating at high speed, it is necessary to produce the spark before the piston reaches the point where the crank is on dead center, if the full force of the exploding gas is to act upon the piston immediately after it passes the center point. On the other hand, if the engine speed is low, the spark may be produced later and the full energy of the exploding gas will still be exerted immediately after the piston passes over upper dead center. When an engine is started it is desirable that the spark shall occur when the crank is practically on dead center. If, however, a high-tension magneto is employed when starting, it is desirable to have the spark occur slightly before the dead-center point. This is particularly true when an electric starter is employed, as the rotational speed of the engine is much higher


L
T
R
GREEN
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C
GREEN
BLUE
RED
BLACK

then than when cranked by hand; and the energy stored in the fly-wheel is sufficient to carry the cranks past the dead-center position.

From the foregoing it will be evident that it is highly desirable to alter the time of firing to suit various conditions. This is accomplished by shifting the housing of the "timer" or "breaker," which will thereby cause the interruption of the primary current and the production of the spark in the cylinder at an earlier or later point in the cycle. A spark-control lever for this purpose is usually attached to the steering column. When starting the engine it is important that the spark should be produced late in the cycle; that is, it should be retarded until after the piston has started on its downward stroke. It is then advantageous to advance the spark as the engine increases in speed. Care should be taken, however, not to advance the spark too far, for if gas is ignited too early the explosion reacts against the piston before it reaches the top of its stroke, which gives a pound in the cylinder and is accompanied by a reduction in power. The most economical position for the spark may be determined experimentally and is reached by advancing the time of firing, so far as possible, without causing the engine to pound. There is a considerable advantage from the standpoint of economy in gas consumption if the greater part of the combustion takes place while the crank is passing the upper dead-center position. Any portion of the combustion which takes place before the crank reaches dead center is not only wasted but is a hindrance. On the other hand, if the combustion is unduly delayed, the full energy contained in the fuel will not be realized in the explosion stroke of the engine and less actual work will be done.

The rate at which a given charge will be ignited depends upon the quality of the fuel and the mixture. A weak mixture or too rich a mixture will burn more slowly than one which is properly proportioned. Fuel possessing a large percentage of heat units will also burn more rapidly than one low in heat value. The real governing factor in determining the rate at which combustion takes place is the intensity of the heat generated. A spark at the plug ignites the gas immediately adjacent thereto. The heat thereby produced is transmitted to the surrounding charge and this burns, transmitting heat to succeeding layers of adjacent gas. The greater the intensity of the heat generated the

greater will be the rate of propagation. The pressure employed also influences the rate of combustion. When a charge is compressed to a very high value in a small space, the heat generated for each cubic inch is greater and the flame has a shorter distance to travel before the whole charge is ignited.

The location of the spark plug also hâs an important bearing on the rapidity with which combustion takes place. If it is situated near the center of the combustion chamber, the whole charge may be fired more quickly than if it is situated on one side. To increase the rapidity of combustion, some engines employ two spark plugs, one over each valve, arranged to spark simultaneously.

Timing Battery Ignition Systems

The type of ignition system used and characteristics of the engine and operating conditions all influence the procedure involved in timing ignition apparatus.

First: Turn engine over, using hand crank until No. 1 piston is at exactly the end of the compression stroke. To determine this position, if no marks are shown on the fly-wheel, proceed as follows: Remove spark plug No. 1 and place a finger over the spark-plug hole, and when the crank is turned the compression stroke can be readily detected in that cylinder. Usually the exact top of stroke may be seen through the spark-plug hole or a wire may be inserted to give an indication.

Second: Put spark lever in "full retard position" and examine the rod and lever connection to the breaker box to see that no excessive lost motion exists. If lost motion is there, a light coiled spring may be attached to keep breaker box arm in proper retarded position.

Third: Remove the high-tension distributor cover and arm, then loosen the clamp screw which holds the breaker cam. Now turn the cam into such a position that it permits the breaker contacts to open and check the amount of opening between the contacts by a standard gauge furnished by the manufacturer; or, in absence of this, set the contacts so that about 0.015 inch space exists when fully open, and secure lock nut on the adjustable contact. Be sure to inspect the contacts for proper alignment and surface contact. Now replace temporarily the high-tension distributor arm and turn until it is directly under or opposite, as the case may be, the high-tension terminal in distributor cover leading

to No. 1 cylinder, thus locating the proper cam lobe for firing No. 1 cylinder. Again remove the distributor arm and locate final position for the breaker cam by turning slightly, in either direction, until the position is reached where the contacts will be just closing, when the back-lash in the distributor gearing is taken up, by turning the cam by hand in the opposite direction to that of normal rotation. The cam should now be securely fastened by its clamp screw. For exact timing, the following absolute check may be applied:

Use a small low-voltage test lamp, which should be connected in parallel with the breaker contacts. As long as the breaker contacts are closed and make electrical contact the lamp will show dark, but will light up with current from the ignition battery, the instant the contacts open. Now turn the hand crank as slowly as possible, stop cranking the instant the lamp lights, then test No. 1 cylinder and see if the piston is at the exact top center on the compression stroke. If the cam is not in proper position, make a correction by readjusting and test again. On engines using dual breakers, as Cadillac, Pierce-Arrow, Stutz, etc., both breakers should open at the same instant to get the best results, it being estimated that one-thousandth of a second difference between the two sparks in the cylinder destroys most of the advantage of the two-spark method of firing the charge. So that, by adjusting one set of contacts first and then using a test lamp across each set of breaker contacts, the second set may be made to synchronize with the first, by adjusting the second set of contacts until both lamps light at the same instant. Now replace the distributor arm and note with which high-tension terminal it is in contact. Then attach the wire from No. 1 plug to that distributor terminal. Attach the other-high tension leads to the other terminals so that the proper firing order will be observed. Be sure the high-tension leads are connected to suit the proper direction of rotation of the distributor arm. The above method is satisfactorily applied to timing of such systems as require removal of the cover of the distributor to adjust the position of the cam in the primary breaker housing.

Such systems as the Connecticut do not require the removal of anything to time properly. In this system, all that is necessary is to loosen the set screws that hold the distributer shaft (they are outside of the breaker box), then slowly turn the breaker

cam in normal direction until you get a spark at No. 1 plug, having previously turned on ignition switch and retarded spark lever. Then fasten the set screws again on the distributer shaft.

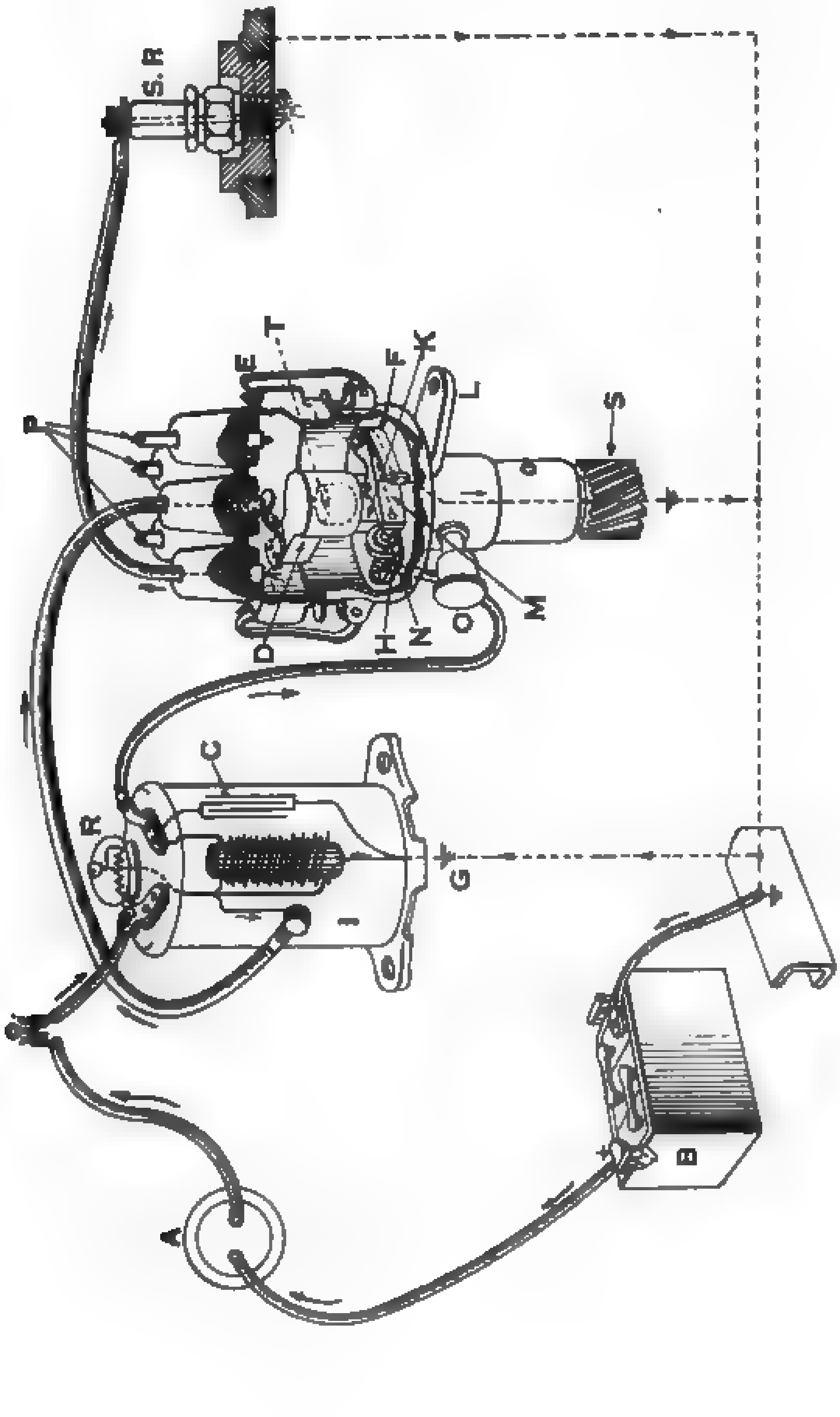


FIG. 970.—Wiring circuits for non-vibrating jump-spark coil and high-tension distributor.

Modern Battery Ignition Systems

The principal parts in a modern ignition system are a storage battery, an induction coil of the non-vibrating type, a breaker and a high-tension distributor. The storage battery supplies current for the starting and lighting system as well as for ignition. The high-tension distributor and the breaker for the low-tension circuit are combined in a single unit, driven either through spiral gears from the same shaft which drives the generator or by a special shaft provided for the purpose. The usual location for the induction coil is on top of the charging generator and close to the breaker and distributor which are frequently carried on one end of the generator. The switch for controlling the ignition circuit may be combined with the lighting switch or constructed independently. It is located on the instrument board. Fig. 970 represents the circuits through a standard automobile ignition system of this type. The breaker-contact points and distributor are both operated by a vertical shaft, and the distributor arm is carried on the upper end immediately above the cam which operates the breaker points. On engines of the four-stroke-cycle type it is necessary that the entire number of cylinders, whether there be four, six, eight or twelve, shall fire in two complete revolutions of the crank shaft. In one revolution of the crank shaft it is therefore necessary that one-half of the total number of cylinders must receive an ignition spark and fire. An ignition system must therefore deliver two sparks for a four-cylinder engine, three sparks for a six-cylinder engine, four sparks for an eight-cylinder engine, and six sparks for a twelve-cylinder engine within each revolution of the crank shaft. To accomplish this it is necessary to employ a cam having four, six, eight, or twelve lobes for lifting the breaker arm and interrupting the primary circuit. The high-tension distributor must have as many segments as there are cylinders, equally spaced from each other so that the high-tension current may be directed to the plug in the proper cylinder at the right time. This system requires that the cam in the breaker housing and distributor arm in the distributor shall be driven at camshaft speed—that is, one-half crank-shaft speed.

As the spark in the cylinder is produced at the moment when the breaker contacts open, it is absolutely necessary that the lobes of the cam operating these contacts shall be accurately

spaced so that the spark in each cylinder will occur at relatively the same point in the revolution. Since the distributor shaft revolves at one-half crank-shaft speed, the segments in the distributor and the lobes on the cam must therefore be spaced so as to correspond to one-half of the angle through which the crank shaft passes during the period between successive explosions in the cylinders. This angle between successive explosions is 180 degrees for a four-cylinder engine, 120 degrees for a six-cylinder engine, 90 degrees for an eight-cylinder engine, and 60 degrees for a twelve-cylinder engine. As 360 degrees comprise one complete revolution, it is a simple matter to determine the angle between successive explosions by dividing 720 degrees, which comprise two revolutions, or one complete cycle, by the total number of cylinders which the engine contains. Thus the angle in a four-cylinder engine between explosions is $\frac{720°}{4} = 180°$.

The Timer

The object of the breaker or primary interrupter is to close and open the primary circuit and thereby magnetize and demagnetize the core of the induction coil so that a spark may be produced at the plug at the proper time. If a non-vibrating coil is employed, this secondary spark will be produced at the moment when the contact points **open.** These points are usually made of an alloy of tungsten and platinum, one being fixed in position while the other is attached to a pivoted arm so it may swing under the pressure of the cam. The points are normally held in contact with each other by means of a spring. As the distributor shaft revolves, each lobe in turn forces the contact on the movable arm away from the stationary contact, opening the circuit at the points about 0.02 inch. As this circuit opens, the current in the primary of the induction coil falls, and the resulting collapse of the magnetic flux of the core upon the secondary winding induces a high-voltage current which is led to the spark plug. The contact points of the breaker are of a non-oxidizable material and designed to stand a high temperature so that they will last a long time even though subjected to more or less heat, due to sparking. A condenser is employed in shunt with these contacts, however, to suppress the sparking as much as possible.

The Distributor

The distributor has an insulated central terminal which passes through the head and connects with the high-tension terminal of the induction coil. Equally spaced around the interior of the insulating housing of the distributor are as many metal segments as there are spark plugs. Distributor heads were formerly made of hard rubber, but they are now generally made of bakelite or some other composition which does not deteriorate under the influence of heat or oil. A carbon brush is usually provided on the inside of the distributor head which is held by a spring in contact with the rotating arm on one side and connects with the high-tension cable on the other side. This device provides a sliding connection between the cable and the moving arm. This arm, also of bakelite, is designed to fit upon the revolving shaft in only one position, so that it may always be brought in contact with the proper stationary segment when the time for a particular cylinder to fire has arrived. In some forms of distributors, the revolving arm has another carbon brush or metal button on its end which actually wipes across the stationary contacts. In other forms this arm simply moves close to, but does not actually touch the stationary segments. As the e.m.f. on this circuit is between 5,000 and 10,000 volts it is not essential that the revolving member actually touch the stationary segments, for the voltage is sufficient to easily jump the gap.

Two spring clips are provided for holding the distributor head in position. These are arranged so that the head can readily be removed for adjustment or inspection. If the revolving arm actually makes contact with the stationary segments, the cap should be removed after the car has traveled one or two thousand miles, and the path through which the moving member travels should be wiped clean of any dirt or carbon deposit which might cause internal short-circuit. A cloth to which a little heavy oil or vaseline has been applied should be employed for this purpose.

Compensating Resistance Unit

On closed-circuit ignition systems the induction coil is provided with a resistance unit which may be seen at *R* in Fig. 970, being usually mounted on the end of the coil. This unit consists of a few convolutions of high-resistance wire, such as nichrome or German silver. This wire possesses a positive temperature

coefficient—that is, its resistance will increase when it is heated up. If the ignition switch is left in the "on position" when the engine is standing still and the breaker contacts closed, the current passing through the induction coil is led through this resistance unit in series therewith. The unit will heat up immediately and at the same time increase its resistance to such an extent as to substantially reduce the flow of current from the battery through the primary winding of the coil. This protects the coil against damage from overheating and at the same time reduces the rate of discharge from the storage battery. The coil is designed to stand the large current required for ignition purposes momentarily but is not designed to carry such current continuously. The duration of each individual closure of the breaker contacts is very brief. If the speed of the engine is high, the contacts remain closed for a short time; if the speed is low, the duration of closure is greater. The longer the time which the contacts are closed the greater the current. The resistance unit will therefore be heated slightly, and the current will automatically be reduced. This tends to equalize the intensity of the spark at high and low-engine speeds. Should the voltage of the battery fall, this resistance unit assists the coil to produce a hotter spark, for it will not serve to check the current until it has reached such a value as to raise the temperature of the unit.

Testing Induction Coils

To determine the condition of the induction coils it is necessary that they be tested. As they are generally sealed with a hard wax they can only be examined from the outside.

To test a vibrating coil a low reading ammeter capable of a range from 0 to 3 amperes should be connected in series with the coil and a 6-volt battery. The secondary terminals should be brought to within ¼ inch of each other by means of wires. When the circuit is completed through the primary winding the vibrator should operate freely and give a good, strong spark. The screw on the vibrator should now be adjusted until the current absorbed is between ¾ and 1 ampere. This should result in a good, heavy discharge across the secondary gap. If the discharge is yellow or feeble, it indicates a weak coil or improper adjustment. If you can blow the spark out with your breath, it indicates an improper adjustment of the vibrator.

If the primary is consuming its proper current and the vibrator operating and yet no secondary spark is obtained, it indicates the probability of a break inside the coil.

Should the ammeter indicate an abnormally large current, it is probable that the primary winding has become short-circuited or that the vibrator contacts are stuck together. With the coil operating properly a very faint spark will generally appear on the vibrator contacts. If this spark becomes blue in color and large in volume, giving off a snappy sound, it indicates that the condenser within the coil is probably open-circuited. The vibrator points will then become rapidly pitted and will soon be unworkable.

Non-vibrating coils have very little to get out of order. Some types contain the safety spark gap and condenser in the same housing with the coil, but either or both of these may be located elsewhere in the system. To test a coil of this type one end of a piece of wire should be attached to any part of the engine frame and the other end should be brought to within about ¼ inch of the high-tension terminal of the coil. If the breaker contacts in the interrupter are then opened, a good, sharp spark should jump between the high-tension terminal and the grounded wire. This will indicate that the coil is in good condition. Failure to secure a spark under these conditions indicates a defect within the coil, such as a short circuit in the primary, an open circuit in the secondary winding, or a failure in the condenser. As has already been set forth, the condenser is connected in shunt with the breaker points in a non-vibrating coil, and across the vibrator contacts in a vibrating coil. It is of ample capacity to absorb the e.m.f. of self-induction, thus preventing the piling up of charges on the primary contact points, so as to form a spark or arc. The secondary spark will be most effective if the condenser acts properly. Should the condenser break down or be removed, it is practically impossible to get a secondary spark suitable for firing.

The tin-foil layers in the condenser may be punctured by a high-voltage discharge and the breaker contacts in shunt therewith be thereby short-circuited, or the connections to the condenser terminals may be broken, thereby opening the circuit. If the condenser is short-circuited, the primary circuit cannot be opened, for the short-circuit therein bridges the breaker contacts. No spark can therefore be produced at the spark plug. If the

circuit to the condenser is broken, it is not permitted to absorb the e.m.f. of self-induction, and the secondary spark is feeble.

The condition of the condenser can usually be determined in the following way: Open and close the contacts at the breaker points and observe the quality of the spark produced across a ¼-inch gap in the secondary circuit. If a good, thick, blue spark is obtained in the secondary circuit and there is no objectionable spark at the breaker contacts, it may be assumed that the condenser is in proper condition. If, on the other hand, the secondary spark is feeble and considerable spark is observed at the breaker points, it is probable that the condenser is open-circuited. If no spark is produced in the secondary when the breaker points are opened, while at the same time current flows in the primary, it may be assumed that the condenser is short-circuited.

Automatic Spark Advance

In some automobile systems the advancing or retarding of the spark is cared for automatically, being governed by the speed of the engine. This relieves the driver of the responsibility of changing the setting of his spark during ordinary driving. In one form of device for advancing the spark, the governor has a revolving weight which is carried on the distributor shaft below the cam which operates the breaker. The entire mechanism is arranged so that the weights move outward against the resistance of a spring, and as the engine speeds up the cam and ring are shifted forward with respect to the timer shaft.

With the manual spark advance the operating lever is placed on the steering column and the proper position is determined by the judgment of the operator.

SECTION XVIII CHAPTER II

AUTOMOBILE ENGINE IGNITION, STARTING, AND LIGHTING

MODERN BATTERY IGNITION

1. Explain the action of a vibrating induction coil for ignition purposes. Sketch.

2. Explain the action of a non-vibrating induction coil for ignition purposes. Sketch.

3. Explain the construction and object of the low-tension timer.

4. Explain the general scheme of the ignition system employed on Ford automobiles. Sketch.

5. Explain why it is desirable to alter the time of firing in an auto engine.

6. Explain how to "time" the firing of an engine using a battery ignition system.

7. What are the principal parts of a battery ignition system with a high tension distributor for a four-cylinder engine? Sketch complete circuit.

8. Is the ignition spark produced when the timer contacts open or close? Why?

9. Of what material are the timer contacts made? Why?

10. Explain the construction and advantages of the high tension distributor.

11. Explain the object and construction of the "compensated resistance unit" on an induction coil.

12. Explain how to make the proper adjustment of a vibrating induction coil. Approximately what amount of current should such a coil consume?

13. Explain how to determine whether the condenser in an ignition system is open-circuited, short-circuited or in good condition.

SECTION XVIII CHAPTER III

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

Magnetos

Magnetos are used extensively for ignition purposes on automobiles of all kinds. They consist of two parts: the field structure, composed of laminated compound steel permanent magnets, and the armature, on which is placed a winding designed to revolve within the field and thereby produce the ignition current. There are two general types of magnetos; (1) The type with a wound armature, the core of which is usually of "H" construction, and (2) the inductor type. In the first, the conductors themselves revolve in the magnetic field. In the second, the conductors are stationary, and the rotor produces the necessary alteration in the magnetic flux.

Magnetos may also be classified as either high-tension or low-tension, depending upon the voltage which they generate. Both of these types may have either a revolving armature or they may be of the inductor type.

Low-Tension Magnetos

In the low-tension magneto the armature winding is of coarse wire, usually about No. 18 gauge, and the voltage generated is low. In order to raise the potential to a suitable velue for ignition purposes, it is nécessary to employ an induction coil. This coil must have a low-tension winding which receives current from the magneto and a high-tension winding in which the requisite voltage for ignition is generated.

The high-tension magneto combines in one structure the elements of generator and transformer. No external induction coil is therefore required. The windings, which correspond to the primary and secondary of the induction coil, are both placed upon the armature of the magneto. The condenser, to care for the spark at the breaker contacts, is also frequently carried within the armature housing.

A distinction should be made here between the true high-tension magneto and the type manufactured by some companies in which a transformer coil is placed outside of the mag-

neto and the armature has a low-tension winding. This type is sometimes designated as a high-tension magneto. But it is not in the proper application of the term.

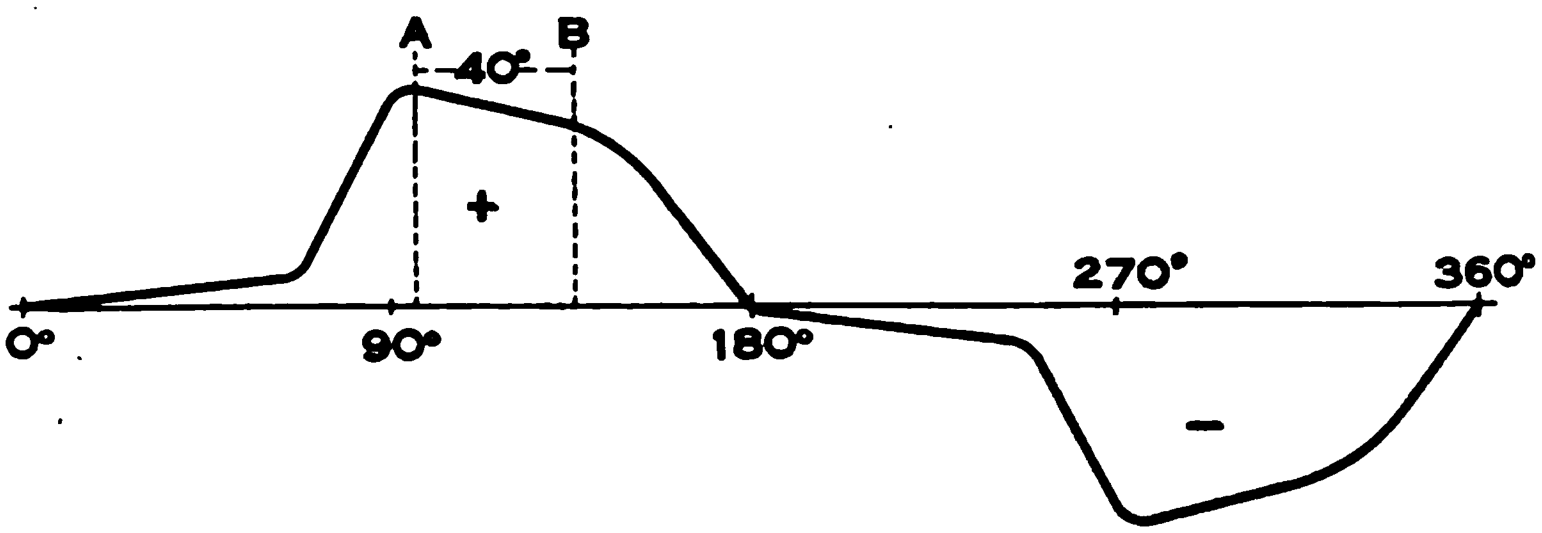


Fig. 971.

Revolving armature magnetos require sliding contacts in order to collect the current. In the inductor type no such sliding contacts are necessary, as the windings are stationary.

Fig. 971 shows a wave of current produced by the ordinary "H" type of magneto armature, sometimes called "shuttle-

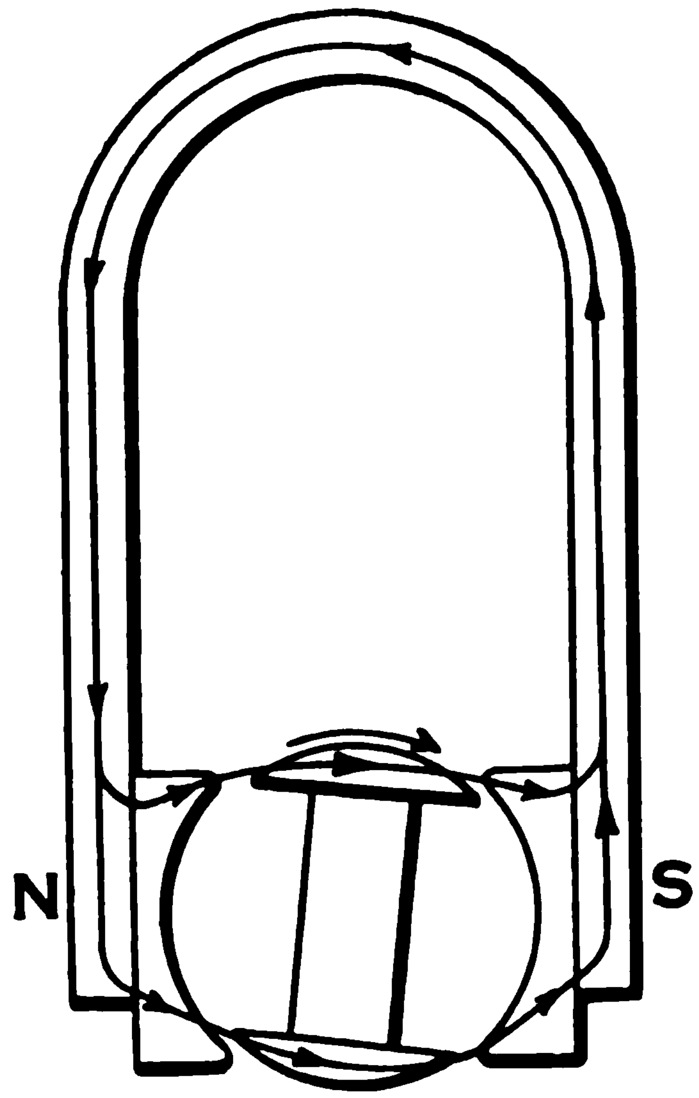


Fig. 972.

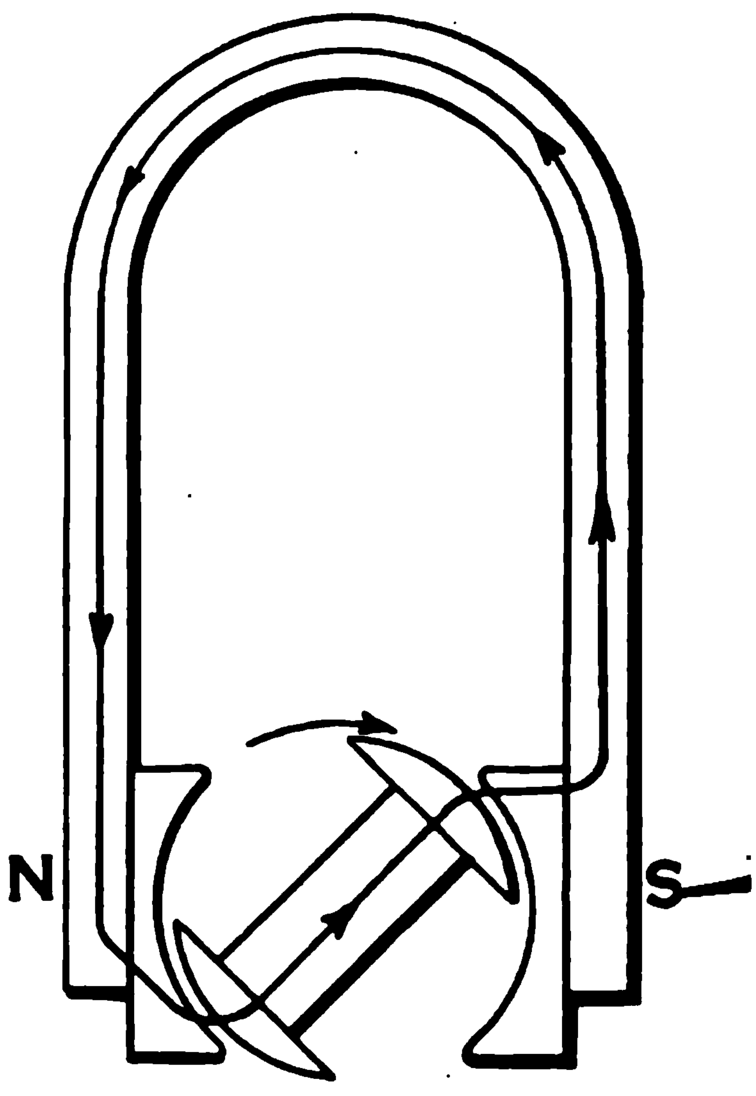


Fig. 973.

wound" because it is wound like a shuttle. There is a considerable departure from the sine wave of e.m.f. produced in large alternators. It is evident that only a portion of this wave is useful for ignition purposes as during the rest of the time the

voltage is not sufficiently high. The effective range is between the dotted lines *A-B* and represents an arc of about 40 degrees. The actual position of the armature when the current is of a maximum value as shown at *A* is illustrated in Fig. 972. The actual position of the armature when the current has fallen to *B* is shown in Fig. 973. It is only through this range, therefore, that current may be obtained for ignition purposes. The position in Fig. 972 represents the extreme point of spark advance and the position in Fig. 973 the point of extreme retard. Because of the shape of the core, any further advance ahead of Fig. 972, or retard beyond Fig. 973, would give too low an e.m.f. to produce a suitable spark.

It is therefore necessary to have the magneto driven by gears from the engine shaft so that the armature will never vary in its proper relation to the position of the cranks and the proper time for firing. As the current reverses in each half-revolution it is evident that there are two ranges during which a spark may be obtained; one, Fig. 971 in a positive direction, and one in a negative direction. Thus, two sparks may be obtained for each revolution of the armature. In a four-cylinder automobile engine this necessitates the armature revolving at crank-shaft speed. It will therefore produce four sparks while the crank shaft makes two revolutions. With a six-cylinder engine it is required that the magneto shall make three revolutions during two revolutions of the crank shaft.

Where a low-tension magneto is employed with an external transformer for raising the voltage, provision is usually made for using a dry battery as an alternative source of supply instead of the magneto. The batteries can be used for starting when the speed of the magneto is low and also for running in case of emergency. As the breaker employed for magnetos maintains the circuit closed during most of the cycle, the life of the batteries would be short if the same breaker was employed. It is usual, however, to provide connections in the switch so that an interrupter is in series between the battery and the coil. In this case the spark is induced by the interrupter rather than by the breaker. In some dual systems a push button is employed in connection with the switch for the purpose of operating a vibrator so that the spark may be produced without cranking the engine. If an explosive charge happens to be in the cylinder through which the spark is directed, the engine may start.

The Ford Magneto. -The magneto universally employed on Ford cars is of the inductor type and furnishes an alternating current under a relatively high frequency It is a low-tension machine and supplies current for vibrating induction coils mounted on the dash Fig. 974 shows the magnets which are carried on the fly-wheel and Fig. 975 the stator which supports the coils. There are sixteen coils in the winding carried inside the

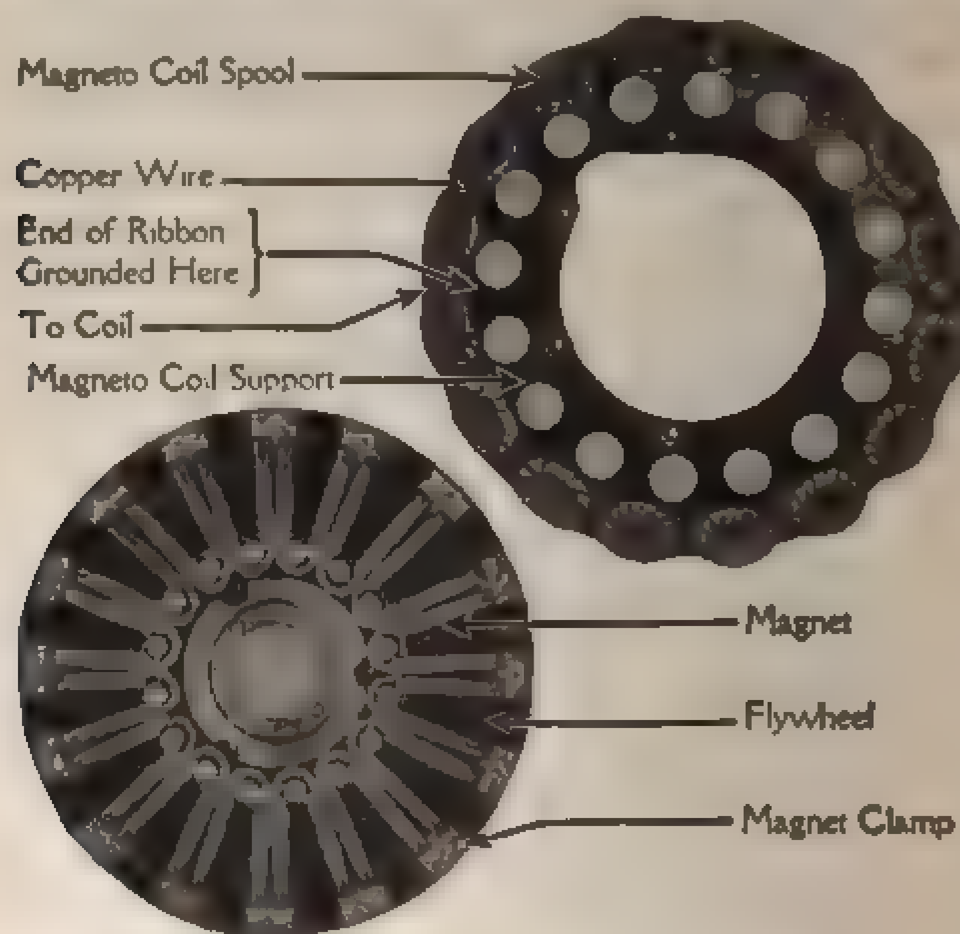


FIG. 974. FIG. 975.
FORD MAGNETO

fly-wheel housing The magnets rotate within a distance of 1 32 inch from the coils. The north poles of two adjacent magnets are fastened together, as are also the next pair of south poles. When a pair of north poles are in front of one of the coils, the magnetic flux passes through the core of one coil, through the plate which supports the coil and out through the core of the adjacent coil to the south poles The current reverses every time the fly-wheel makes 1 16 of a revolution. This results in sixteen current impulses for every revolution of the fly-wheel. At 1,800 r.p m , or 30 miles per hour, this means a frequency of 240 cycles per second All the coils are connected in series, and one end of

the circuit is grounded on the engine frame. The other end leads through an insulated binding post to the outside of the engine. From this terminal a circuit leads to all four of the induction coils through a metallic plate for the purpose, located in the bottom of the coil box, as shown in Fig. 968. The other four terminals of the coils lead to the four binding posts of the timer, which is carried on the front end of the camshaft. As one side of the magneto is grounded and as the timer completes the circuit through its insulated terminals and the revolving roller to the ground for each induction coil in proper order, it is evident that the magneto current will pass through whichever coil is grounded through the timer. These coils are each provided with two windings and a vibrator.

There is a marked difference between this magneto and those previously described. Because of the high frequency of the current delivered and the fact that successive impulses follow each other very closely, it is not necessary to have the magneto timed with respect to the engine.

The frequency is so high that the variations of the current cause only a slight alteration in the instant when the spark is produced, and there is no practical disadvantage in the fact that the current repeatedly falls to zero. The arc of contact in the timer is sufficiently great to cause one current wave to merge into the next, so that, if the moving magnets are in a position where no current is produced when the timer first makes contact, the crank shaft need move only a very few degrees before the magneto reaches a position where it will generate sufficient current to induce a discharge from the coil. It is therefore only necessary to rotate the housing of the timer to vary the ignition of this system. It is customary to fix the point of firing so that contact will be made in the timer of cylinder No. 1 when the piston in that cylinder is about 1/8 inch below dead center on the explosion stroke when the spark-control lever on the starting wheel is in the full retarded position.

High-Tension Magnetos

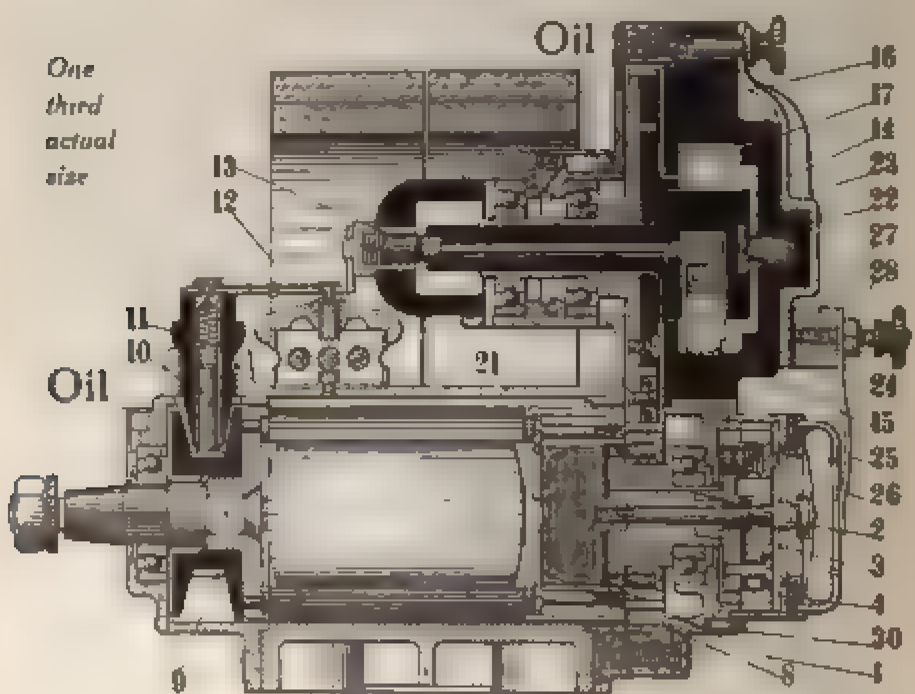
As has already been stated, the high-tension magneto is a self-contained machine in which the requisite high voltage is produced for jumping the gap in the spark plug without the aid of any external-induction coil. The armature winding consists of two sections, a primary and secondary, which are connected to

each other. The interrupter is attached to the end of the magneto shaft and the distributor is geared immediately above it.

The Bosch Magneto.—One of the most widely used magnetos is the Bosch. A sectional view of this machine, showing the principal parts, is given in Fig. 976. It has an armature of the "H" type mounted on ball bearings. As will be seen in Fig. 977, the armature contains a primary winding of a few convolutions

1. Brass plate.
2. Contact breaker screw.
3. Platinum screw block.
4. Contact breaker disc.
5. Long platinum screw.
6. Contact breaker spring.
7. Contact breaker lever.
8. Condenser.
9. Slip ring.
10. Carbon brush.
11. Carbon holder.
12. Connecting bridge.
13. Contact carbon.
14. Rotating distributor piece.
15. Distributor carbon.

Longitudinal Section.



16. Distributor disc.
17. Metal segments.
18. Contact plug.
19. Fibre roller.
20. Timing lever.
21. Dust cover.
22. Cover.
23. Triangular clamp.
24. Nut for switch wire (short circuit).
25. Spring for fastening brass cap.

FIG. 976.—Sectional view of Bosch high-tension magneto.

of heavy wire and a secondary winding of many convolutions of fine wire, the latter being wound outside of the primary. A condenser is placed in the end of the armature and revolves with it. The interrupter for breaking the primary circuit is placed on an extension of the armature shaft, and the condenser is placed in shunt with it. The breaker points are separated by means of cams placed on the inside of the interrupter housing. This is a different arrangement from that found on the low-tension magneto, where the cam is carried on the armature shaft and the

breaker on the housing. It is generally considered advantageous, however, to have the breaker, primary winding, and condenser all mounted on the armature shaft, as this gives a very compact and efficient construction.

As indicated in Fig. 977, the first or inner end of the low-tension winding of the armature is grounded on the armature core, and the common connection between the high-tension and low-tension windings is brought out through an insulated path to the breaker contact. A good ground for the magneto armature is

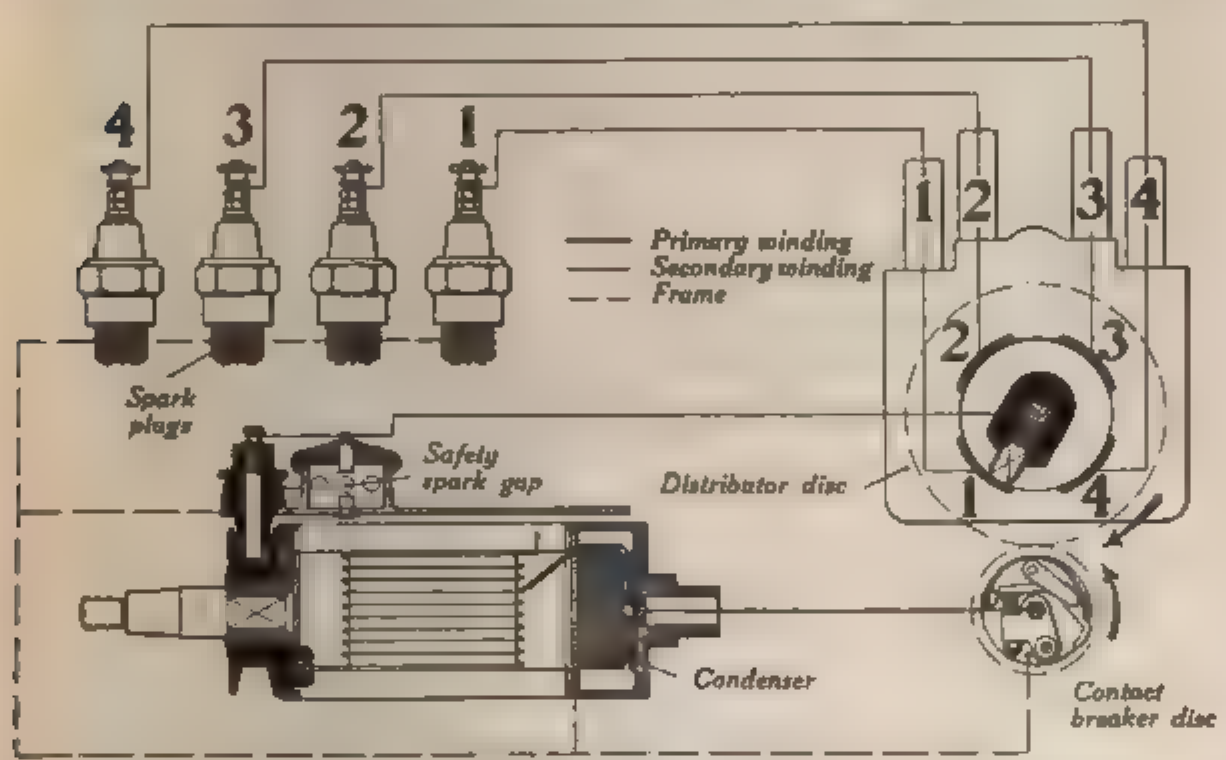


FIG. 977.—High-tension and low-tension circuits for Bosch high-tension magneto

assured by means of a brush which slides on the armature housing and which connects with the frame of the magneto The low-tension winding is normally maintained on short-circuit through the breaker contacts. As the armature revolves, the voltage, and therefore the current generated in this winding, varies from zero to a maximum value. The high-tension winding also generates a considerable voltage, due to cutting of lines of force of the permanent magnetic field. This voltage, however, is not sufficient to bridge the gaps at the spark plugs When the proper time for firing arrives, the breaker contacts open and the short-circuit on the low-tension winding is interrupted. The delivered current is now due to three causes **First,** as the current collapses in the primary winding, due to the opening of the

short-circuit thereon, mutual induction sets in between the low-tension and high-tension windings. **Second,** the generated voltage in the secondary winding, due to the rotational effect of the armature. This e.m.f. is in the same direction as that generated in the secondary winding by mutual induction. **Third,** to whatever extent mutual-induction fails between the low-tension and high-tension windings due to leakage, to precisely this extent self-induction ensues in the primary winding. As the low-tension and high-tension windings are in series, the e.m.f. of self-induction and the e.m.f. of mutual induction all combine to aid the voltage due to generator action in the secondary winding, and a veritable flame is produced at the spark-plug points of such intensity that it may properly be characterized an arc. Magnetos of this type have sometimes been designated "arc light" machines because of this action.

To stop the engine, a switch is employed which permanently short-circuits the low-tension winding. This kills the e.m.f. of both mutual-induction and self-induction, and the normally generated secondary e.m.f. is not sufficient to bridge the spark gap at the plugs.

The magneto armature is driven through gears at crank-shaft speed, while the distributor above it is geared for cam-shaft speed, which is one-half of crank-shaft speed. When the interrupter housing is in the fully advanced position, the armature should be in the position shown in Fig. 972, at the moment when the breaker contacts open. It is then possible to shift the timing lever between 30 and 40 degrees, which will rotate the housing of the breaker contacts to the full-retard position. This insures that a spark of maximum intensity will be produced when the engine is running at normal speed and the housing set for full advance.

Referring to Fig. 977, the outside terminal of the high-tension winding of the armature leads to a highly insulated slip-ring on the back of the armature, on which is placed a carbon brush. This brush collects the high-tension current and leads it through a rod to the center of the distributor, where contact is made with the revolving arm. The high-tension current is then directed to the proper cylinders in order. After passing to the engine frame, the current returns via the grounded circuit to the frame of the magneto, thence through the armature core to the inside end of the low-tension winding.

When a high-tension magneto is assembled it is important that the gears between the armature and distributor should be set with the proper relation so that the distributor arm will make contact in the housing with the proper segment at a time when the interrupter points break the circuit in either the advance or retard position. The span of a distributor segment is made sufficient to accomplish this purpose. When the spark is set for full advance, the brush in the distributor should be just coming in contact with a given segment, and when the breaker contacts open, the brush should be just leaving the same segment with the interrupter housing shifted to full-retard position.

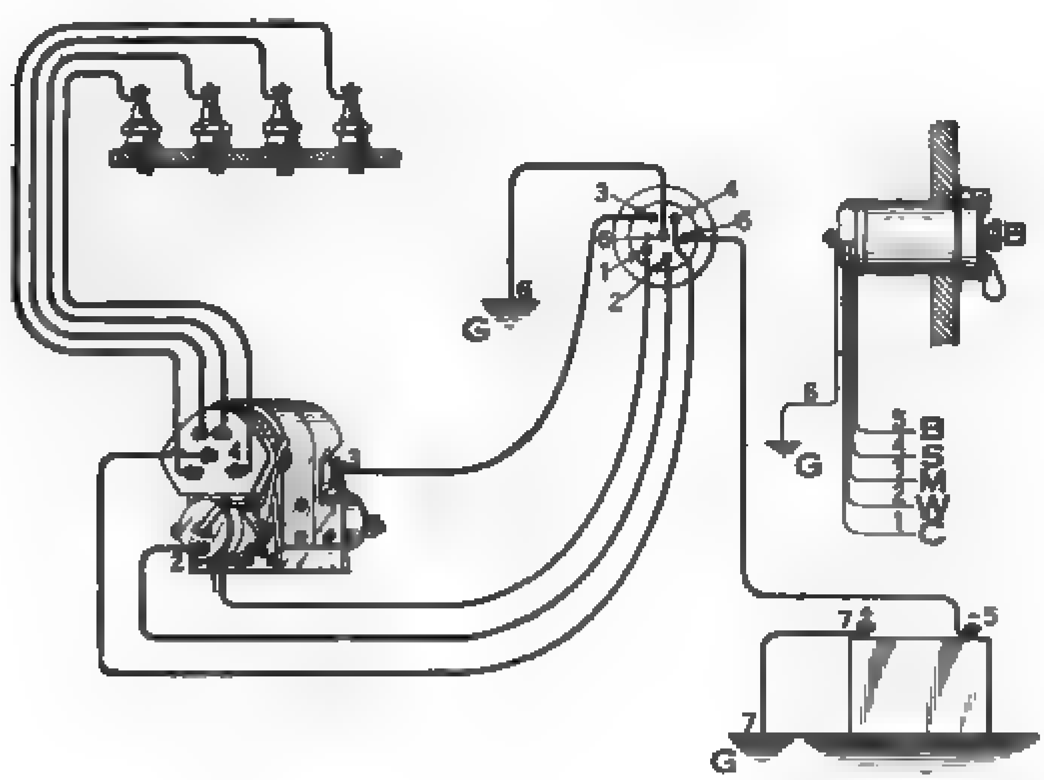
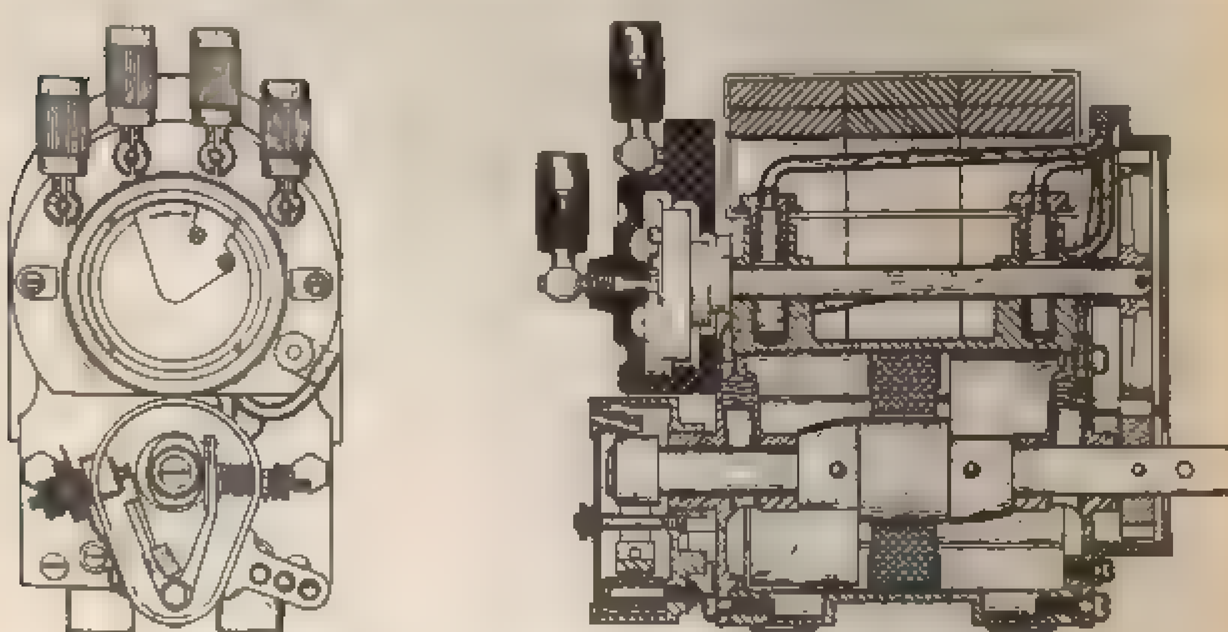


FIG. 978.—General arrangement of circuits for Bosch system of dual ignition.

Because of the high voltage generated in this type of magneto it is necessary that a safety gap be provided to prevent puncture of the armature insulation or the breaking down of the condenser in case the circuits leading to the spark plugs should be interrupted. This gap is shown in Fig. 977, placed just above the armature at the rear. The contact points which are placed across the high-tension circuit are separated about 5/16 inch. Sparks should not be permitted to jump these contacts continuously, as there is danger of injuring the armature winding or breaking down the condenser.

The Bosch Dual System.—In the Bosch dual-ignition system a standard high-tension Bosch magneto, carrying two sets of breaker contacts, is employed. Attached to the armature shaft is a disk with two segments, through which the current is collected. The rollers or cams are carried on the interrupter housing. The magneto is also provided with a steel cam, having two projections and built into the interrupter disk. This cam operates a lever carried on the interrupter housing and is connected in the battery circuit, so as to serve as a primary interrupter for the battery current When the battery is used, a non-vibrator transformer coil is employed to step up the voltage. The induction coil used with this system is mounted in a brass case and arranged to be attached to the dash board The wiring



End View of Magneto. Longitudinal Section of Magneto

FIG. 979.—Remy inductor type of low-tension magneto.

for this system is shown in Fig 978 Dual ignition involves more or less complication in wiring and equipment.

The Eiseman Impulse Starter.—Many magnetos do not give a spark of sufficient intensity to fire the engine when cranking by hand. The makers of the Eiseman magneto have overcome this difficulty by a device called an "impulse" starter. This consists of a spring coupling between the source of power and the magneto armature. When cranking, this spring is compressed and the armature positively driven, the coupling being maintained rigid through the medium of a trigger When the time for firing arrives, however, the cam on the trigger ring engages

the one on the tube within and disengages the trigger. This allows the spring, which has already been compressed, to spin the armature of the magneto past the firing point and thus provide a hot spark. When the rotational speed is slow the trigger is caught as it passes the notch, but when the rotational speed is high, as when the engine is firing, centrifugal force prevents the trigger from entering the notch provided for it. A permanent solid connection is therefore provided for driving at high speed. With this type of starter an auxiliary ignition system is not necessary.

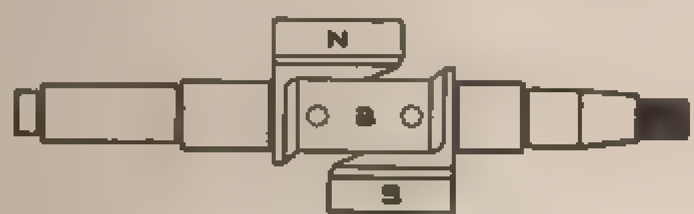


FIG. 980.

The Remy Low-Tension Magneto.—Attention has already been diected to the inductor type of magneto The Ford and the Remy

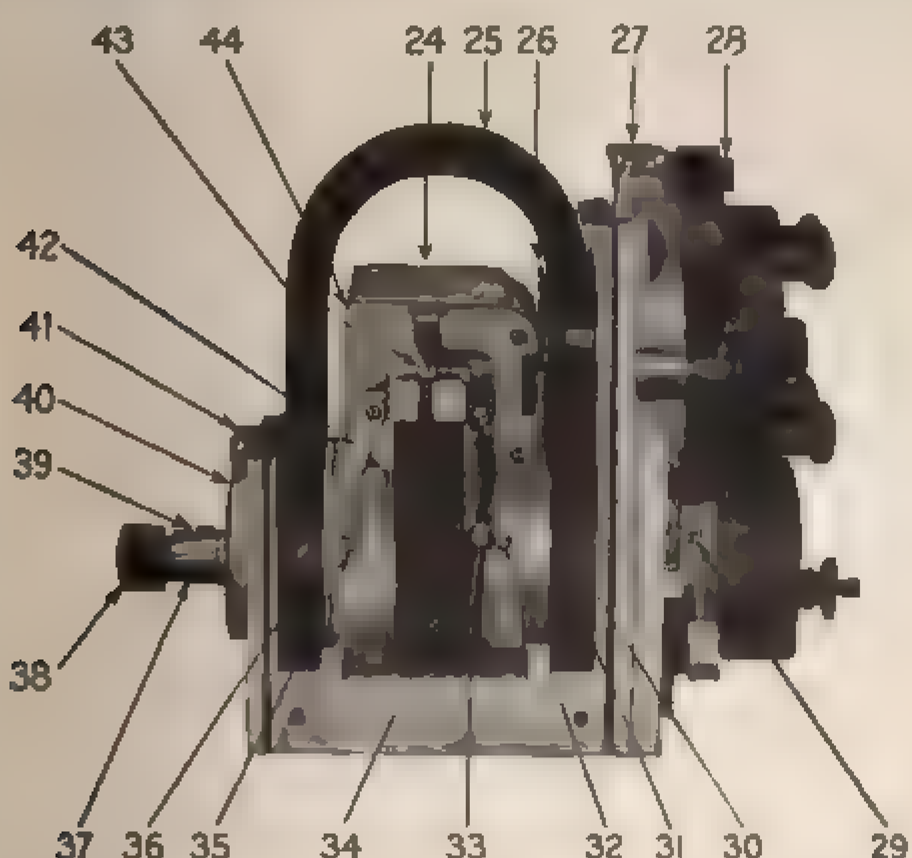


FIG 981.

belong to this class. In the Remy magneto both the coils and the magnets are stationary, the flux being cut by the rotation of an S-shaped rotor within the coil. The reversal of the flux generates the current in the stationary winding. Fig. 979 illustrates the construction of the Remy magneto. All moving wires, carbon brushes and sliding contacts are eliminated. The rotating part is a solid steel shaft carrying two simple forgings or inductor wings, one on each side of the winding. The stationary winding is directly connected through a circuit breaker with the primary of a non-vibrator coil. The design of the rotor is such that the current wave is considerably prolonged, allowing a range of timing something over 60 degrees of the inductor's revolution.

The Dixie Magneto.—One of the most unusual types of inductor magnetos is the Dixie, invented by Charles T. Mason. This machine is manufactured by the Splitford Electric Company. The magneto consists of a pair of magnets, a field structure, a stationary winding, a rotor, a circuit interrupter and a condenser. The rotor carries two wings, *N* and *S*, Fig. 980, separated by a bronze casting, *B*. The polarity of the wings is al-

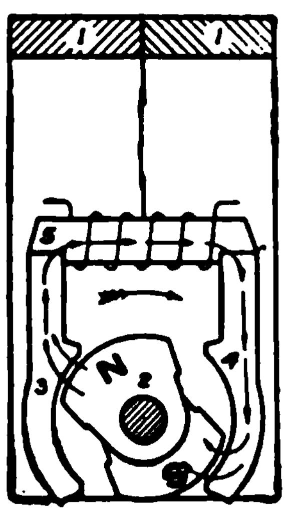


FIG. 982.

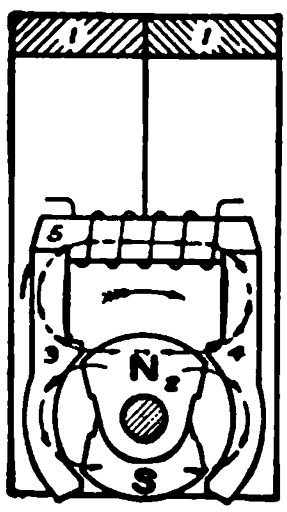


FIG. 983.

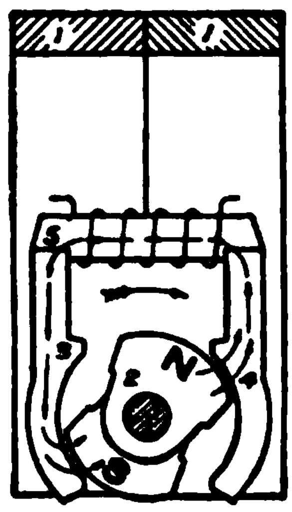


FIG. 984

ways the same, for the magnetism never reverses therein. The rotor in revolving allows the magnetic flux to circulate through the core of the winding in alternating directions, according to the position which the rotor occupies with respect to the poles of the field structure. A view of this magneto with cover removed is shown in Fig. 981.

In Fig. 982 it will be noted that the path of the flux through the coil is from left to right. In Fig. 983 the flux does not pass through the coil at all, while in Fig. 984 the flux passes through the coil from right to left. When the magnetic flux is changing

in the core of the coil at a maximum rate, the highest voltage and therefore the greatest intensity of current will be induced. This occurs in the position shown in Fig. 983. This is the point where the interrupter contacts should open the primary circuit. Fig. 985 gives a very clear idea of the magnetic circuit. A diagram of the electrical circuits for this magneto is given in Fig. 986. When the primary circuit is broken, a high-voltage current is induced in the secondary winding, this current being directed to the proper spark plug by a geared distributor carried above the rotor shaft.

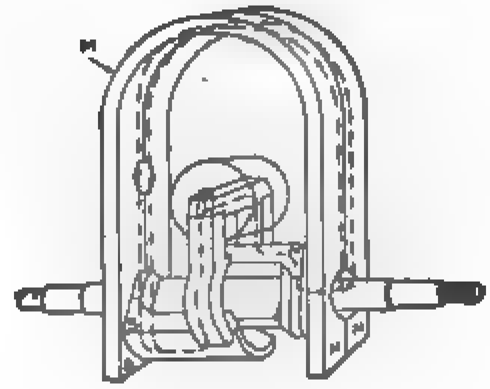


Fig. 985.

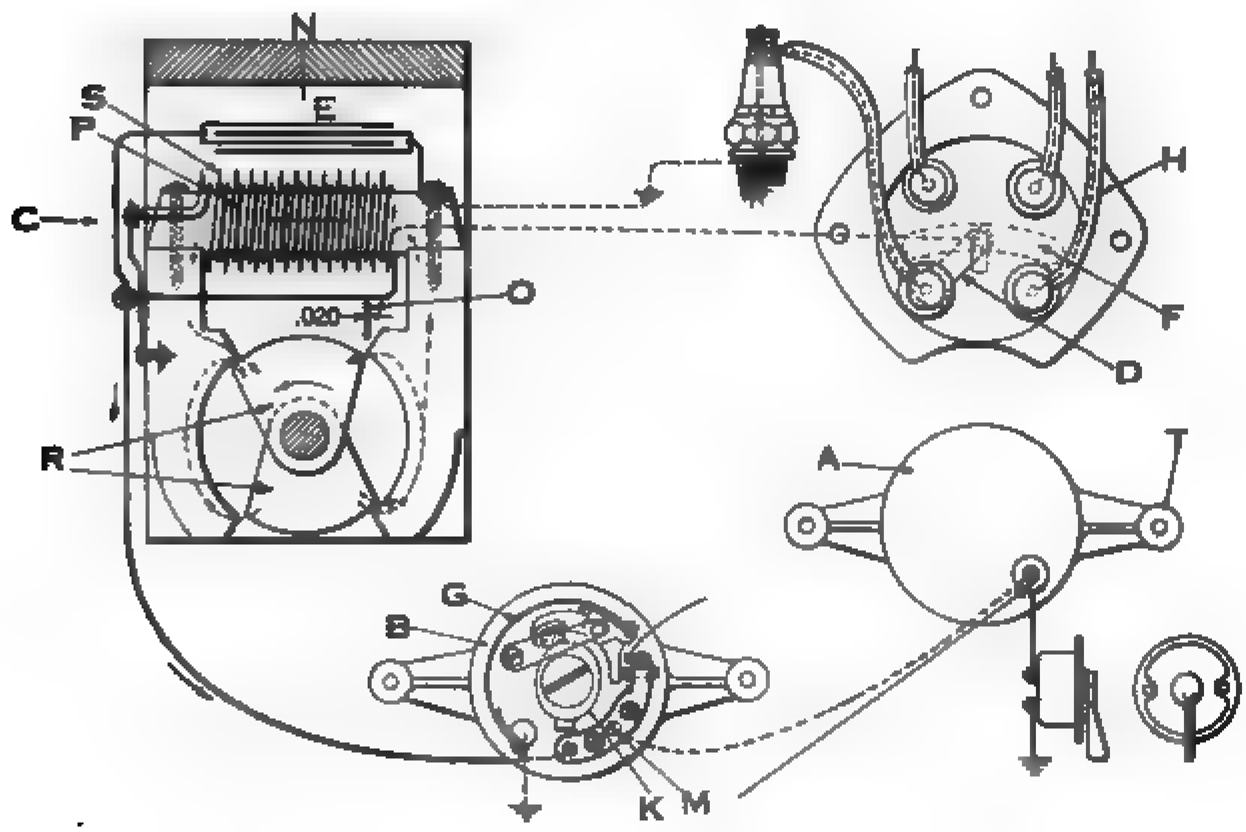


Fig. 986.—General arrangement of coil and circuits in Dixie inductor-type magneto.

An unusual feature found in this magneto is the ability to shift the pole pieces together with the timing lever for the purpose of retarding or advancing the spark. This allows the breaker contacts to open the primary circuit when the primary current is at its maximum value regardless of the position of advance or retard.

Magneto Timing

As already stated, engines of the four-stroke-cycle type require four strokes of the piston or two revolutions of the crank shaft to complete the cycle. In Fig. 987 an attempt is made to show these two revolutions, and to illustrate what occurs in each portion of the cycle. The crank is supposed to be rotating anti-clock wise and the piston moving vertically. Consider the piston at the top of its stroke and about to start downward. After the crank has moved through an angle of approximately 10°, the inlet valve must open. The suction stroke of the engine now begins, and the inlet valve should close between 20° and 30° after the crank passes the lower dead-center point. This necessitates the inlet valve remaining open through an angle of between 180° and 200°. The crank now moves upward, compressing gas in the top of the cylinder as both inlet and exhaust valves are closed. Somewhere between 5° and 10° before the crank reaches the upper dead-center point, the gas is ignited and combustion begins. Within an angle of from 5° to 10° the combustion should be completed. It is important that the full energy of the exploding gas shall be exerted upon the piston head just as the crank passes the upper dead-center position and as the piston starts downward on the explosion stroke. During this stroke the gas expands. Somewhere between 30° and 40° before the crank reaches the lower dead center-point, the exhaust valve should open, thus permitting the gas to be forced out of the cylinder on the return stroke. This valve should close a few degrees after the crank has passed the upper dead-center point. Another cycle is then started.

When an engine is being cranked it is necessary that the ignition point should be delayed until the piston passes the upper dead center. This is to avoid an early explosion, forcing the crank backward. To delay the firing, the spark must be retarded. When the engine gets under way, the spark should be advanced until it takes place at the proper time, as indicated in Fig. 987. Complete combustion of the full charge does not occur instantaneously but requires a considerable fraction of a second for its completion. At high speed the piston may move a considerable distance during this interval. This is the reason that the spark must be produced a few degrees in the cycle before the crank reaches the upper dead-center point, in order to allow

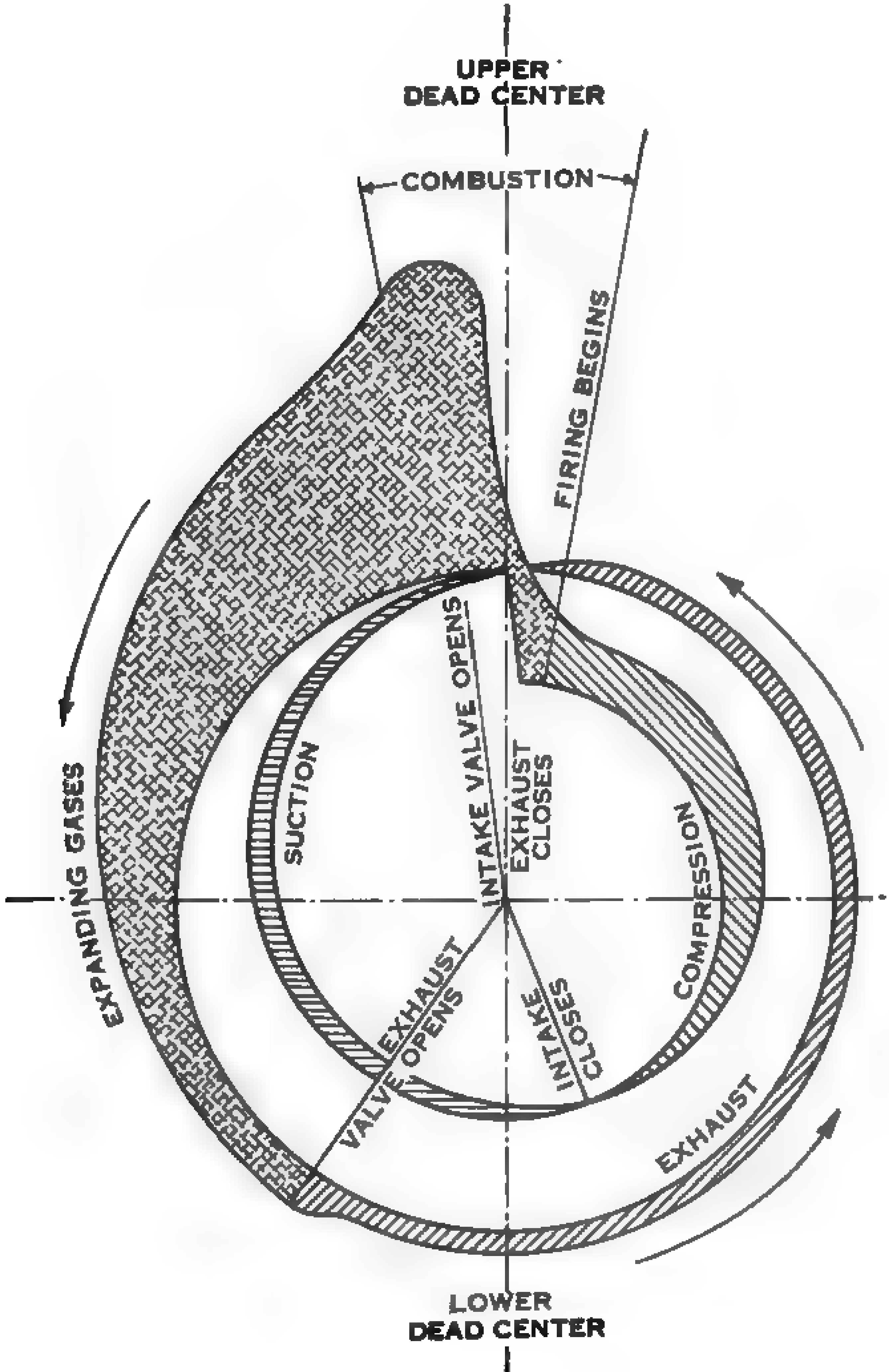

UPPER
DEAD CENTER
COMBUSTION
FIRING BEGINS
EXPANDING GASES
SUCTION
INTAKE VALVE OPENS
EXHAUST
CLOSES
COMPRESSION
EXHAUST
VALVE OPENS
INTAKE
CLOSES
EXHAUST
LOWER
DEAD CENTER

Fig. 987.

time for the mixture to burn and the full pressure to develop before the working stroke begins. The faster the engine runs the more the spark should be advanced, while the slower it runs the more the spark should be retarded. This is the reason that the time of firing must be controlled either by a lever operated by the driver or by some mechanism which provides for an auto-

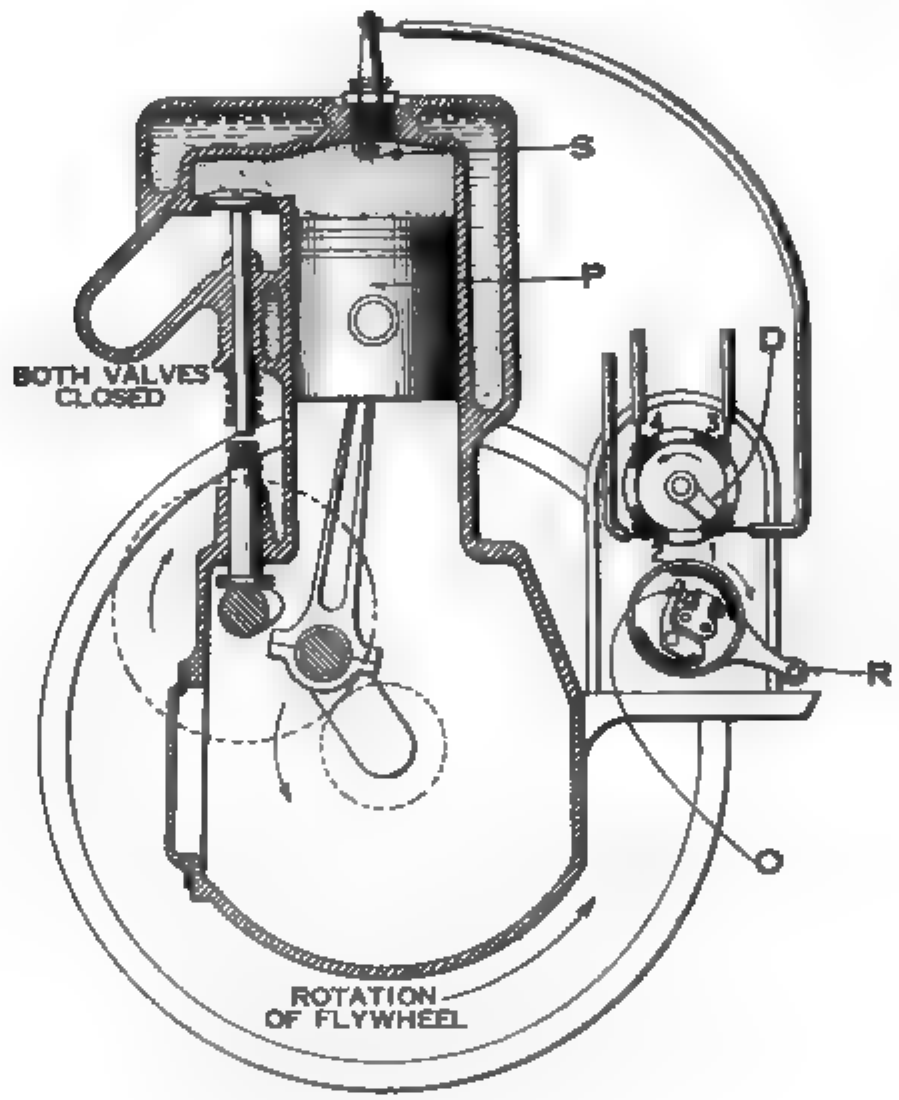


Fig. 988.—Relative position of make-and-break high-tension distributor and circuits at the moment of firing charge in engine.

matic adjustment of the spark. The adjustment of the spark to the proper point is called "timing."

In Fig. 988 a view is given of cylinder No. 1 in an automobile engine, with the crank in the proper position for the explosion stroke. The charge is compressed in the top of the cylinder and the crank is about to descend. The inlet and exhaust valves are both closed. The flexible coupling connecting the magneto to the driving shaft should be loosened, and the armature of the magneto should be rotated in its proper direction until the brush in the distributor is in contact with segment No. 1, which in turn

should lead to the spark plug in No. 1 cylinder. The spark lever should now be placed in the fully retarded position and the armature shaft rotated until the cam is just about to separate the contact points in the breaker housing. This is as shown in cut. The crank at this time should be exactly on dead center. With the magneto positively held in this position the coupling should then be tightened. The other spark plugs should then be wired to the distributor in the order in which the engine is designed to fire. When the spark lever is placed in its fully retarded position, the magneto will fire the charge sufficiently late to make hand cranking safe, and from this point the spark may be advanced as the speed of the engine requires.

SECTION XVIII CHAPTER III

AUTOMOBILE ENGINE IGNITION, STARTING, AND LIGHTING

MAGNETOS

1. Explain the general principle of the magneto employed for ignition purposes.
2. Explain the actual construction of a low-tension magneto.
3. Explain the construction of a semi-high tension magneto.
4. Explain the construction of a straight high tension magneto.
5. Explain the construction of the inductor type magneto.
6. May magnetos be belt-driven or must they be positively geared? Why?
7. Give sketch of current wave produced by a magneto and show through just what range the current is of sufficient magnitude for ignition purposes.
8. Explain the construction of the Ford magneto.
9. Explain the construction of the Bosch high tension magneto.
10. Give sketch of wiring for a Bosch high tension magneto for a four-cycle engine, including all interior and exterior circuits.
11. In order to stop the engine, how is the ignition circuit rendered inoperative when supplied by a high tension magneto.
12. Explain the general plan of the Bosch dual ignition system.
13. Explain the construction of the Remy low tension inductor type magneto.
14. Explain the principle of operation and construction of the Dixie high tension magneto. What are its advantages?
15. Explain in detail the method of adjusting the timing of a magneto.

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

Starting and Lighting Systems

During the development of the gasoline automobile many different devices have been designed and put on the market for cranking the engine until it was able to operate under its own power. Among the more successful of these were the mechanical starter which was operated by the driver from the seat; air starters, which admitted compressed air from a storage tank to the engine cylinders; acetylene starters, by means of which the driver could inject a small quantity of acetylene gas into the cylinders for starting on the spark; and electric starters, which crank the engine by a small electric motor, deriving power from a storage battery carried on the car.

The electric starter has practically replaced all other types of starters and is now furnished as standard equipment on practically all passenger cars and on many trucks. The essential parts of a typical electric starting and lighting system are a small D. C. motor for cranking the engine; a storage battery to supply current to the lights when the generator is not being operated and current to the starting motor for cranking the engine, and a D. C. generator for charging the storage battery.

Electric starting and lighting systems may be divided into two general classes according to the number of individual units used to perform the starting and generating functions. In the **single-unit** system the starting motor and generator are combined into one unit known as a motor-generator. It draws current from the storage battery for cranking the engine, and after the engine begins to fire and operate under its own power with increasing speed, the motor-generator automatically becomes a generator and sends current back into the battery.

In the **two-unit** system the starting motor and generator are built as separate units. The generator is permanently geared to

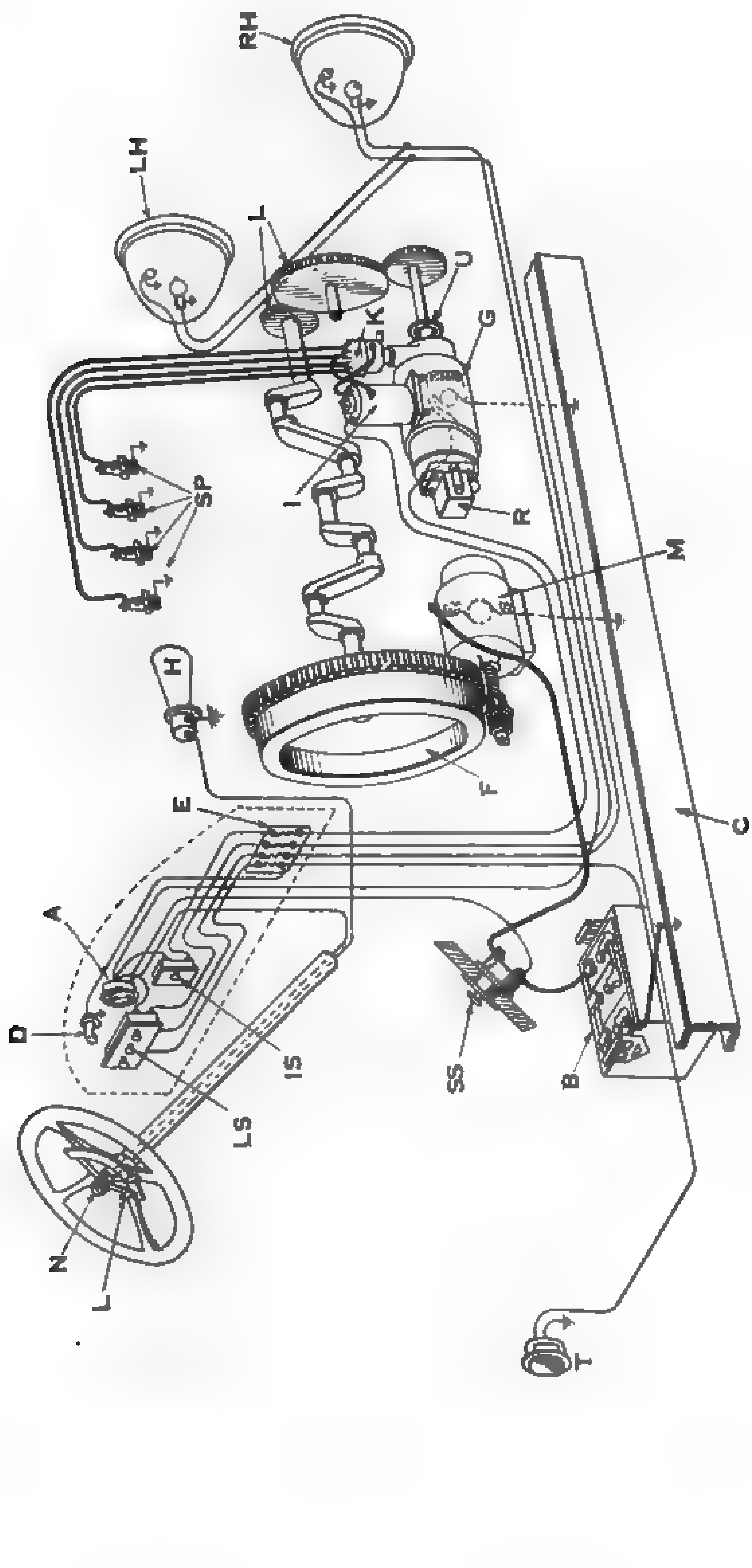


FIG. 988-A.—General location of charging generator, starting motor, storage battery and electrical circuits for two-unit system of automobile starting.

the engine and driven continuously by it. The starting motor is normally disconnected from the engine through the driving mechanism and operates only when the starting switch is closed and the starting gears brought into mesh.

Another type of starting and lighting system, which is a compromise between the single-unit system and the two-unit system, is the Delco motor-generator system. This machine is provided with two separate sets of armature and field windings, with individual commutators similar to the two-unit system, but employs a single field structure and armature core and therefore has a magnetic circuit similar to the single-unit system. This system has been brought to a very high degree of mechanical perfection and is used on many high-grade cars.

Fig. 988-A illustrates a typical installation of a two-unit starting and lighting system, showing the proper relation of the different units to each other. This is a single-wire or ground-return system and employs the framework of the car to carry the return current from the starting motor, generator, lights, ignition, and horn back to the negative side of the battery. The single-wire system is now almost universally used in preference to the two-wire system as it greatly simplifies the wiring of the car, although it has the disadvantage that a single ground on the insulated side of the system has the same effect as a short-circuit on a two-wire system and renders the grounded unit inoperative.

The voltage used on the older systems varied from 6 to 24 volts; but at the present time 6 volts are used almost universally for starting, lighting and ignition purposes. The higher-voltage systems have the advantage that smaller currents are handled and therefore smaller wiring could be used and still not have an excessive drop between the battery and starting motor. The lower-voltage systems have the advantage that a smaller and less expensive battery may be used, but also have the disadvantage that larger currents must be handled, requiring larger cables between the battery and the starting motor.

It is also very important in the lower-voltage systems that the resistance of the starting circuit and its connections shall be kept as low as possible. Corrosion at the battery terminals may increase the resistance at that point to such an extent that the starting system may fail to work at all. When the starting

switch is closed the initial rush of current on a 6-volt system may be as much as 250 amperes. Should a resistance of only 0.01 ohm be encountered in the circuit, 250 amperes passing through it would involve a loss of 2.5 volts, and this would leave only 3.5 volts to be applied to the motor. It is therefore obvious that if the energy of the battery is to be realized in the starting motor, the resistance of the starting circuit must be maintained as low as possible.

A few systems still operate with a 12-volt battery, and in some cases it is arranged so as to be divided into two groups and con-

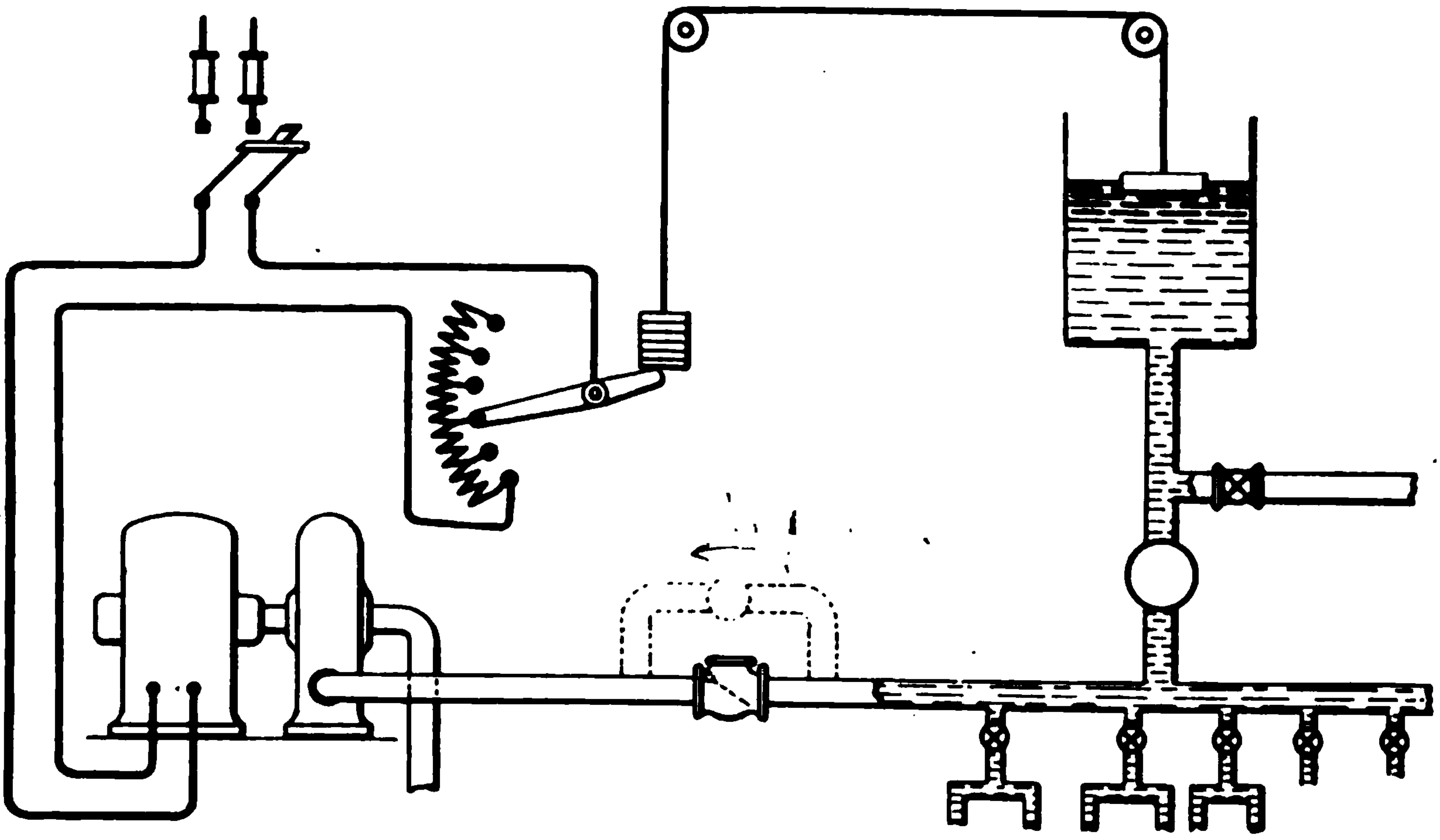


FIG. 988-B.—Storage of water in reservoir corresponding to the storage of electrical energy in a battery.

nected in parallel while being charged, using the higher voltage for starting purposes only.

The principle of operation of the different units of the starting and lighting system may be compared to the operation of an automatic water system as shown in Fig. 988-B. The pump is driven by a motor the speed of which may be controlled by an adjustable resistance, which is itself controlled by a float in the main tank or reservoir. The pump is connected through a main to the reservoir which is placed at such a height as to give the desired pressure, and also connects directly to the various outlets so that water may pass directly from a pump to the outlets without first passing through the reservoir. A check valve is

placed in the main line between the pump and reservoir for the purpose of preventing water from the reservoir flowing back through the pump when the pressure from the reservoir exceeds that of the pump or in case the pump should be stopped. If the amount of water being used at the outlets is in excess of that supplied by the pump, the difference will be supplied by the reservoir. This will cause the level of the reservoir to fall, and the float mechanism will move the rheostat in such a way that the motor will speed up and drive the pump faster and increase the supply of water furnished by the pump. If the demand for water at the outlets should decrease below that furnished by the pump, the excess will be forced into the reservoir, and as the level rises the float mechanism will cause the motor to run slower and reduce the output of the pump. In this way the output of the pump is regulated in such a manner as to maintain the reservoir at a constant level regardless of the variable demand for water at the outlets.

The pump in the water system corresponds to the generator in the starting and lighting system which is driven by the engine, the reservoir to the storage battery, the float mechanism to the regulating relay for controlling the output of the generator, and the check valve to the reverse current cutout of the starting and lighting system.

The water meter registers the amount of water flowing into or out of the reservoir and corresponds to the ammeter or current indicator on the electric system which shows the amount of current flowing into or out of the storage battery. If the generator had an output of 10 amperes and the lamps required 5 amperes, then the ammeter would show 5 amperes flowing into the battery; but if additional lamps were turned on until the demand for current reached 10 amperes, then the ammeter would register 0, showing that no current was flowing into or out of the storage battery.

If, now, still more electrical devices are turned on and the total demand for current increased to 15 amperes, then the battery would have to supply the difference of 5 amperes, and the ammeter would show discharge of 5 amperes being drawn from the battery. In all two-unit systems and most of the single-unit systems the current for the starting motor does not pass through the ammeter, as the current supplied by the battery for cranking

purposes is very large and far beyond the range of the instrument. The ammeter used does not usually have a range of more than 20 or 30 amperes and would be burned up by the heavy current. Under normal conditions the generator output should be so regulated that, with all the lights turned on, the ammeter should show a charging current of 2 to 5 amperes passing into the battery which is to compensate for the current drawn from the battery for cranking purposes.

If now a by-pass valve is shunted around the check valve in Fig. 988-B, the analogy of the water system will apply equally well to the single-unit system. The by-pass valve corresponds to the starting switch and, when opened, allows the water to flow from the reservoir around the check valve and operate the pump as a water motor, corresponding to the action of the motor-generator. With this arrangement the starting current will pass through the ammeter, and since the range of this instrument is not sufficiently high to handle this large starting current it is either omitted from the system or replaced by a current indicator capable of carrying a large current. The current indicator does not indicate the number of amperes passing, but simply indicates whether the battery is charging, discharging, or floating across the line.

Generator and Starting-Motor Drives

The position in which the generator is mounted on the engine and the manner in which it is driven depend very largely on the type of engine on which it is to be used, and it therefore represents an individual problem for each different make of car. The generator is commonly driven at a speed of from one to one and one-half times crankshaft speed from the timing gears either by a pinion on the armature which meshes directly with the timing gears or by a silent chain running in oil. In some cases the drive is made by an extension of the pump shaft, in which case a flexible coupling is usually interposed between the generator and pump shaft to insure proper alignment of the bearings.

The starting motor, in most cases, is mounted so as to drive to the fly-wheel of the engine either through gears or by a silent chain. There are three different ways in which the motor may be connected to the fly-wheel for cranking the engine.

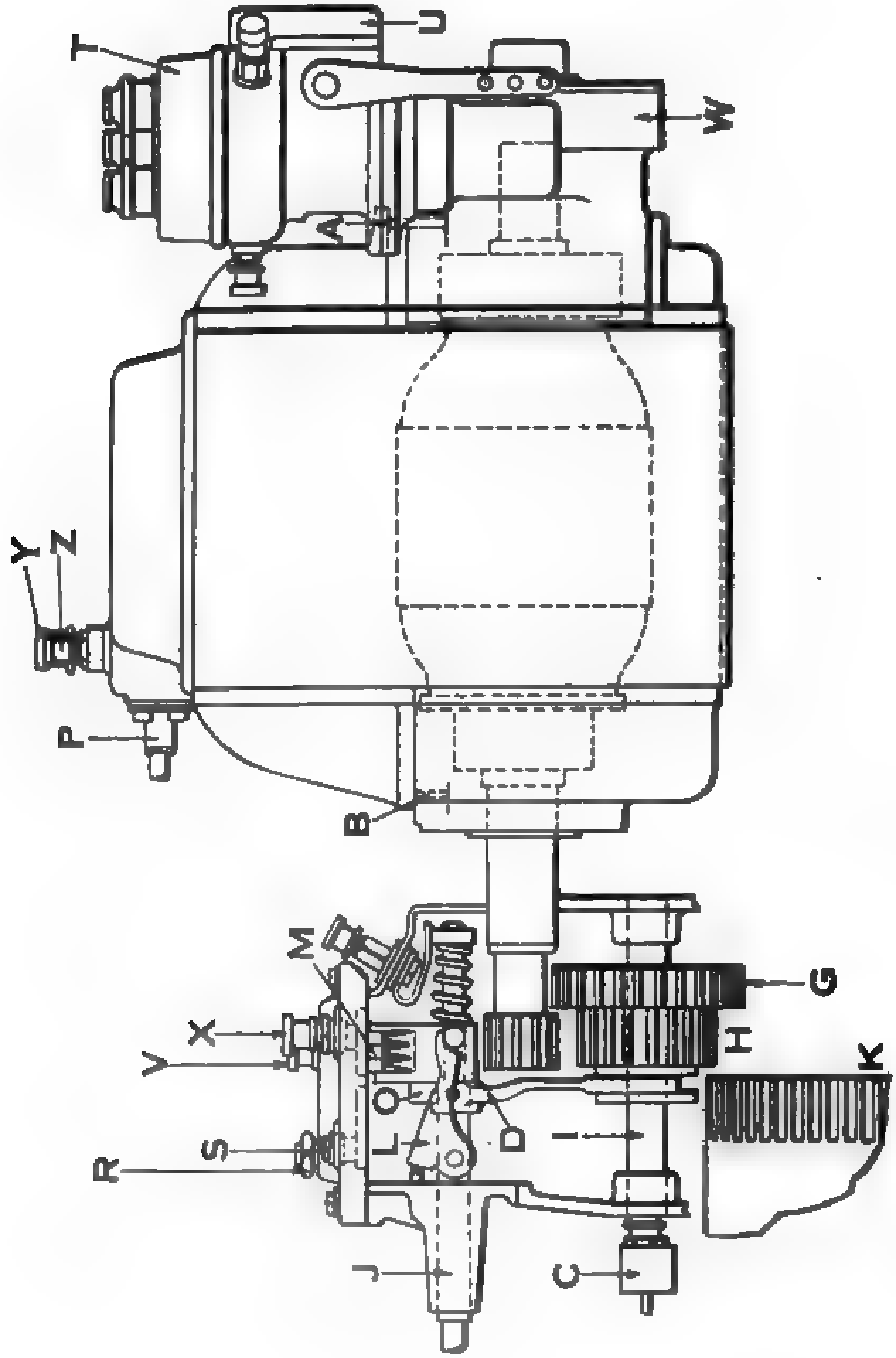


FIG. 288-C.—Delco starter and generator combined showing plan of shifting gears.

1. The sliding-pinion type as shown in Fig. 988-C, in which a pinion or intermediate gear *G-H*, is shifted by the operator as the starting switch is closed.

2. The magnetic type shown in Fig. 988-D, in which the armature *A* and pinion *P* are shifted against the tension of a

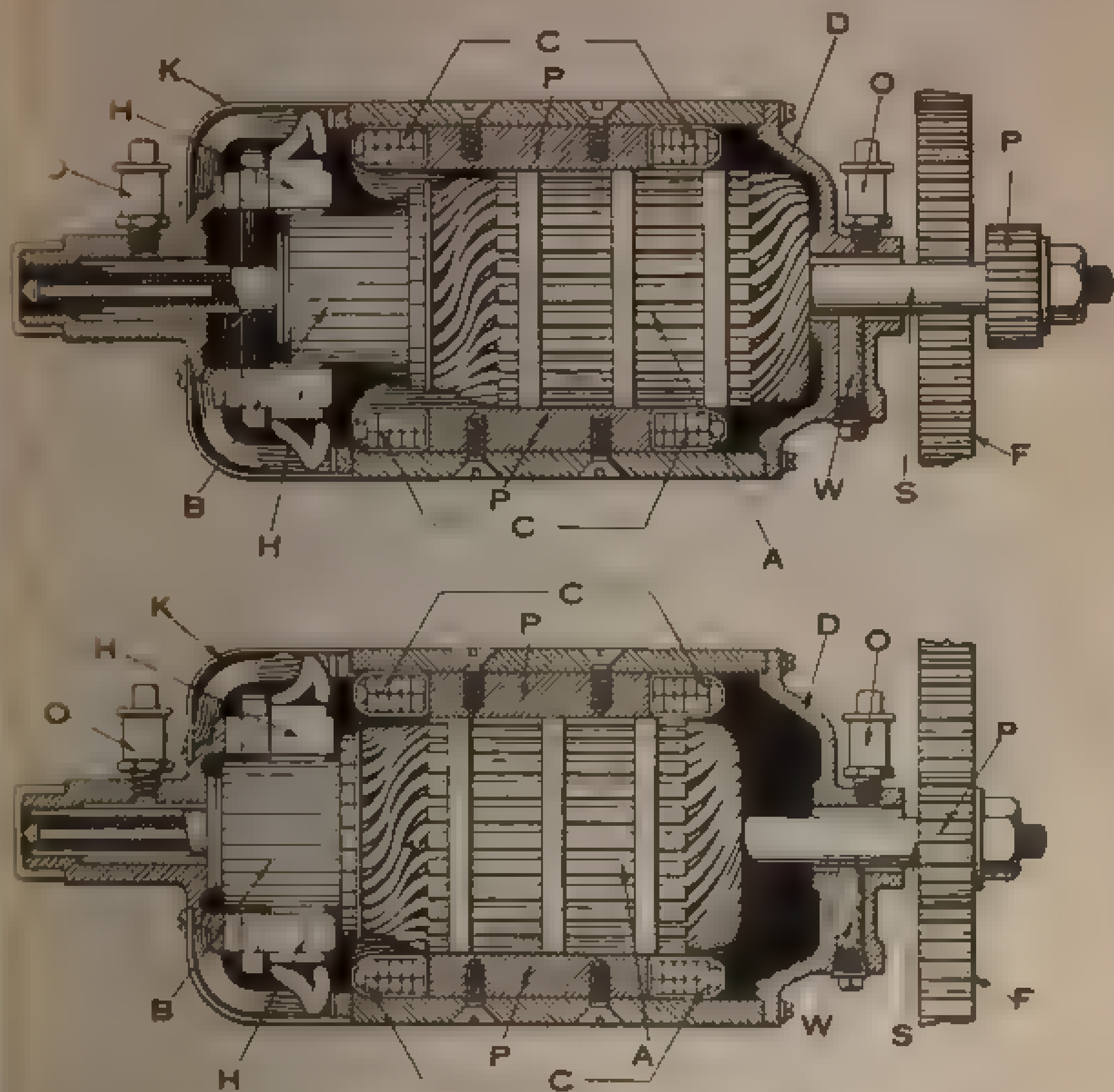


Fig. 988-D. Bosch magnetic gear-shift for engaging armature of starting motor with fly-wheel. Upper view shows pinion disengaged, lower view shows pinion in mesh.

coiled spring by the magnetic pull between the armature itself and the field thus pulling the gears into mesh.

3. The Bendix drive, as shown in Fig. 988-E, which automatically meshes the gears without any skill being required on the part of the operator.

On the systems employing the single-gear reductions, as in Figs. 988-D and 988-E, the pinion on the armature shaft meshes

directly with the gear teeth on the flywheel, and the reduction obtained between the motor armature and the fly-wheel is about 10 or 12 to 1. In some cases where the double-reduction gear is used, as in Fig. 988-C the gear reduction may be as high as 40 to 1.

With the double-gear reduction the pinion on the armature shaft meshes with an intermediate gear, which in turn drives the pinion which meshes with the teeth on the fly-wheel. With the double-reduction drive a much smaller motor may be used,

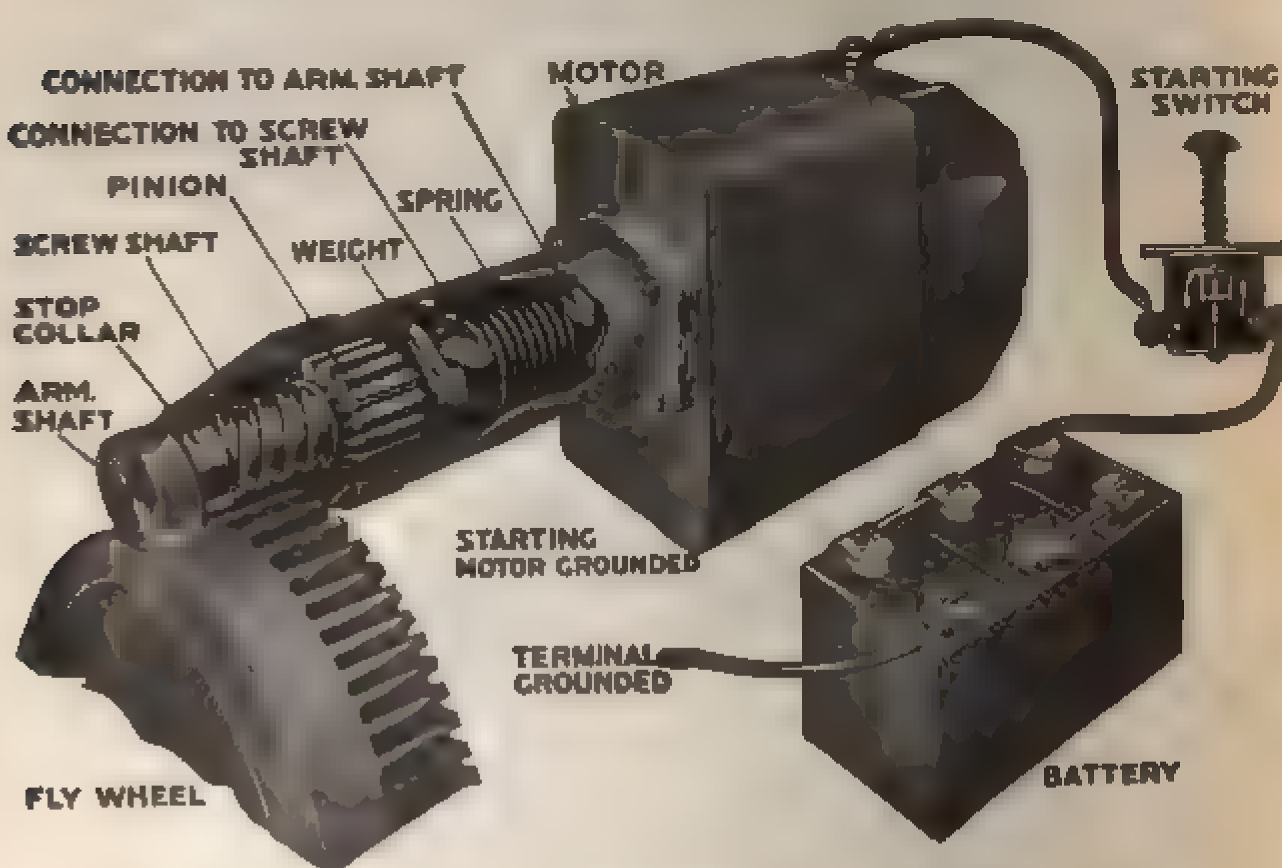


Fig. 988 E.

running at a much higher speed; but it has the disadvantage of having a more complicated driving mechanism.

Owing to the high gear ratio between the starting motor and fly-wheel, some provision must be made to prevent the fly-wheel from driving the starting motor at a dangerously high speed when the engine starts operating under its own power at an increasing speed. For example, assume this gear ratio to be 30 to 1 and that the throttle is half open when the engine is being cranked. As soon as the explosions begin to take place the engine will very soon speed up to about 500 r p m. Before the engine is started, however, the motor will be running near its

safe maximum rate of about 3,000 r.p.m. An electric motor of this type will operate safely at speeds as high as 5,000 r.p.m., but speeds in excess of this are liable to damage it. Under these conditions the motor would be running at a speed in excess of 7,000 r.p.m. A number of different devices have been used for disengaging the starting motor from the fly-wheel, but at the present time the over-running roller clutch is the most widely used. In starters employing the intermediate reduction gear this clutch is incorporated in the intermediate gear itself, Fig. 988-C. Fig. 988-F shows the internal construction of the clutch incorporated within the intermediate gear. It consists of an outer

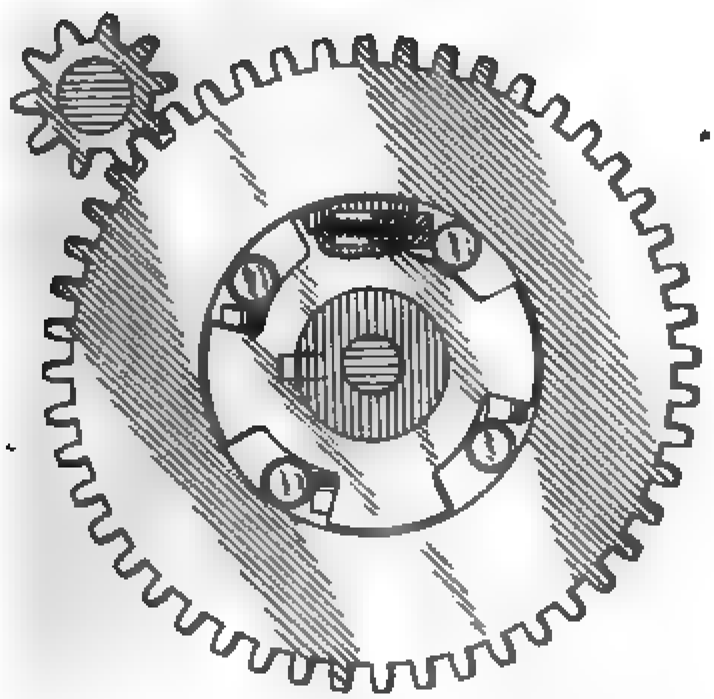


Fig. 988-F.—Overrunning clutch employed by Delco, Gray & Davis, and other companies.

driving member and an inner driven member connected by a number of rollers. The use of a clutch of this type allows power to be transmitted by a train of gears in one direction only, and thus prevents the engine from driving the starting motor at an excessive speed.

On starters using the magnetic or Bendix drive the driving pinion is automatically thrown out of mesh when the engine speeds up under its own power.

The construction of the Bendix drive which is almost universally used on starting motors of the two-unit type is very clearly shown in Fig. 989. This is of the "in-board" type, that is, the pinion progresses toward the motor as it engages the gear wheel. No bearing for the shaft is required at the outer end. A triple-

threaded sleeve P, is mounted on an extension of the armature shaft, having stops at each end to limit the travel of the pinion, G, which, having internal threads corresponding to those on the sleeve, is mounted on the sleeve so as to be free to turn and move along the sleeve, thus shifting the position of the pinion for engaging with and disengaging from the teeth on the fly-wheel. The sleeve is connected to the shaft of the motor armature through a coil spring S, attached to a collar which is fastened to the armature shaft.

The operation of the Bendix drive is shown in Fig. 988-E. This is an "out-board drive," that is, the pinion progresses away from

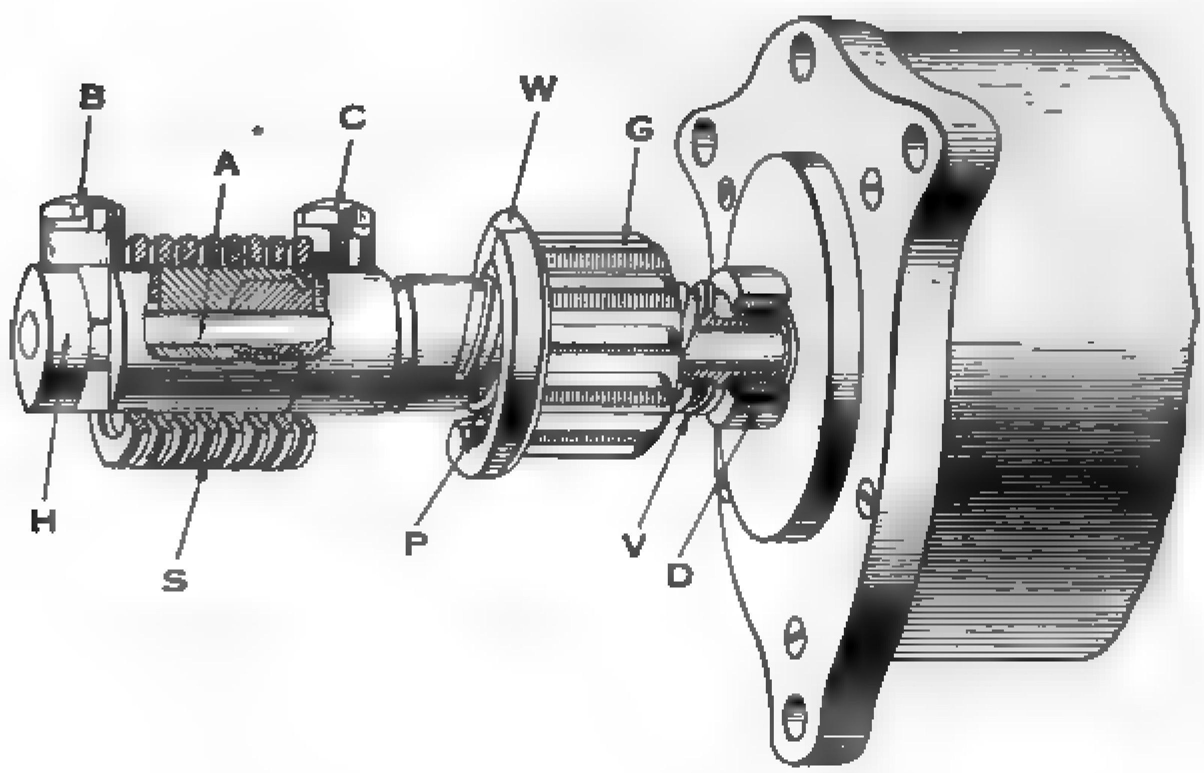


Fig. 989.—"Inboard" type of Eclipse-Bendix drive.

the motor along the shaft to engage the gear and must always have an out-board leaving at the end of the shaft to support it. The pinion normally remains stationary on the sleeve and out of mesh with the fly-wheel; but as soon as the starting switch is closed, the motor immediately begins to rotate at a very high speed due to the full voltage being impressed upon it with no load to prevent its rapid acceleration The pinion is weighted on one side and therefore does not begin to turn immediately with the sleeve; but, having internal threads, will run forward on the revolving sleeve until it meets or meshes with the fly-wheel gear. In case the teeth of the gears meet, the spring will allow the pinion to revolve until it is in proper position to mesh

with the fly-wheel gear. After the pinion meshes, the spring is compressed and the engine is turned over by the motor-driven pinion, it being driven through the spring. The spring acts as a cushion and breaks the severity of the shock on the gear teeth when they are meshed, or in case of backfire. After the engine begins firing, the fly-wheel drives the pinion at a higher rate of speed than the armature, thus causing the pinion to be turned in the opposite direction on the sleeve and to automatically disengage from the fly-wheel, and thus prevent the engine from driving the starting motor at an excessive speed even though the starting switch is not released immediately. After the pinion has been automatically disengaged from the fly-wheel, the centrifugal effect of the pinion holds it at the end of its travel on the sleeve remote from the fly-wheel until the switch is opened and the motor comes to rest.

Among the advantages of the Bendix drive are:

1. Its simplicity of construction and operation.

2. It gives a high cranking speed due to the fact that the starting motor attains practically full speed before the gears are meshed and the load applied. With the higher cranking speed thus obtained the engine will tend to begin firing sooner, thus lessening the drain on the battery and the time during which the starting motor must be in operation.

3. The engine is given a higher break-away cranking torque, which is very desirable in cold weather when the engine is very "stiff" due to the thickening of the oil, and the available capacity of the battery very much reduced due to the drop in temperature.

4. The entire mechanism is automatic in its operation and requires no skill on the part of the operator.

In single-unit systems such as the Northeast and Dyneto, the motor-generator is usually driven by a silent chain from the crank-shaft at two and one-half to three times engine speed.

In the Delco motor-generator the armature is driven independently as a motor and as a generator. When operating as a generator the armature is driven from the timing gears through an overrunning clutch at about one and one-half times crank-shaft speed, Fig. 988-C, but when operating as a motor a pinion on the rear end of the armature meshes with an intermediate gear which in turn meshes with the fly-wheel, thus obtaining a gear ratio of about 20 to 1 for cranking purposes. This change in

the gear ratio is made possible by the use of the overrunning clutch in the generator drive end. Another similar clutch is provided in one of the intermediate gears of the motor drive to prevent the fly-wheel from driving the armature at excessive speed when the engine begins firing.

The Reverse Current Cut-out

The reverse current cut-out, or relay, is an electro-magnetic switch connected in the charging circuit between the generator and the battery. It is evident that, if the storage battery were at all times in direct connection with the generator, it would immediately discharge through the generator windings as soon as the driving speed of the generator fell below the point where sufficient voltage was generated to overcome the counter voltage of the battery. The function of the reverse current cut-out is to automatically connect the generator to the battery when its voltage exceeds that of the battery and to automatically disconnect the generator from the battery when its voltage falls below that of the battery, and thus prevent the battery from discharging back through the generator when it is running at a very low speed or has been stopped. The action of the cut-out is very similar to that of the check valve placed between the pump and reservoir in Fig. 988-B.

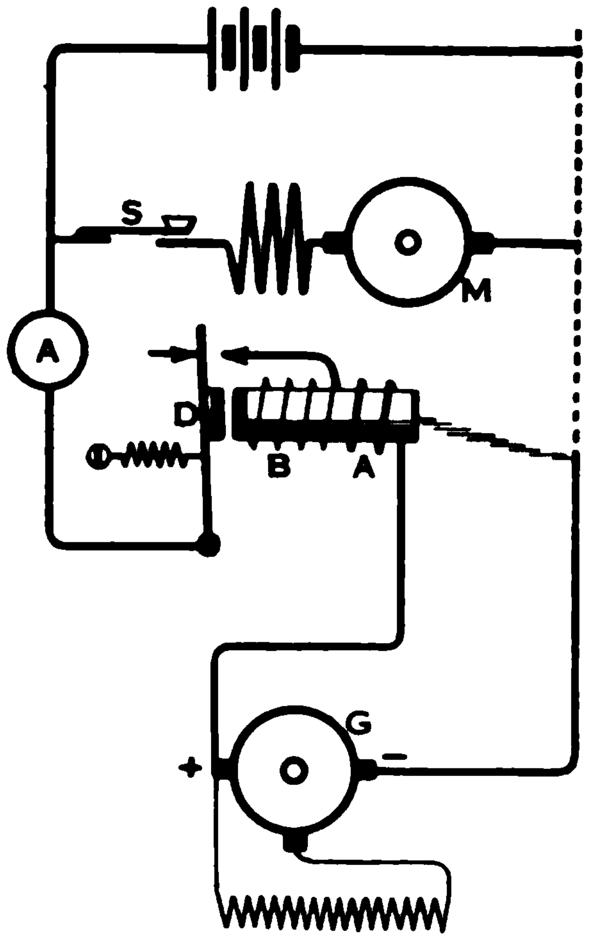


FIG. 990.—Simple wiring diagram for two-unit system showing battery, charging generator, automatic cutout and starting motor.

In Fig. 990 is shown a circuit diagram of a typical cut-out connected to a third brush generator on a two-unit, 6-volt system. The cut-out consists of a soft iron core over which are placed two separate windings, one a potential winding *B*, consisting of a large number of turns of fine wire connected in shunt with the generator, and the other *A*, a current winding, made up of a relatively few turns of large wire and connected in series between the generator and a set of contacts which are closed by the magnetic attraction produced by the shunt winding on the

core. The contacts are normally held apart by a spring and are closed only when the core produces sufficient magnetic pull to overcome the tension of the spring. The tension of the spring should be adjusted so that the contacts will close when the terminal voltage of the generator reaches 6.5 to 7 volts on a 6-volt system, or 13 or 14 volts on a 12-volt system. With the gear ratio most generally used, these voltages are attained at a car speed of 8 to 10 miles per hour, and the generator begins to charge the battery at that speed. The last end of the potential coil is grounded and is therefore connected across the terminals of the generator, and when the generator reaches a speed at which it generates about 7 volts the core is sufficiently magnetized by the current flowing through the potential winding to overcome the spring tension and close the cut-out contacts. This completes the circuit between the generator and battery, and current now flows from the positive terminal of the generator, through the series coil of the cut-out and contacts of the cut-out to the positive side of the battery, and after passing through the battery returns to the negative side of the generator. From the diagram it will be seen that the current flows around the core through the series winding in the same direction as the current flowing through the voltage winding and produces a magnetic effect in the core in the same direction as that produced by the voltage winding. This holds the contacts very firmly together, notwithstanding the severe vibration to which they are sometimes subjected.

If the speed of the generator decreases so that its voltage falls below 6 volts, which is approximately the voltage of the battery, then a momentary discharge current will flow from the battery through the current winding of the cut-out and through the generator. Since the direction of this current passing through the series winding is opposite to that passing through the potential winding, the core will be demagnetized and the contacts opened by the tension of the spring, thus preventing the battery from discharging through the generator windings. The cut-out should be adjusted so that the contacts will open with a discharge current of one ampere or less flowing, preferably as near zero as possible so as to reduce the arcing at the contacts when they are opened.

The ammeter is usually connected as shown in order that it may indicate the amount and direction of current flowing in either direction between the generator and battery. The car

speed at which the cut-out contacts open should be 2 or 3 miles below the speed at which they close, in order to prevent the continuous opening and closing of the contacts in case the car should be driven at the critical speed at which the contacts operate. The car speed at which the contacts open and close may be determined by slowly increasing and decreasing the car speed and taking the speedometer reading at the instant that the ammeter shows a charging current, and again when it returns to zero. In case the lamps have been turned on they will increase in brilliancy at the instant that the cut-out closes, due to the voltage on the lamps being increased to 7 or 7.5 volts instead of 6 volts as when the cut-out opens and disconnects the generator from the battery and lamp circuit.

Regulation of Charging Generators

The generators used with starting and lighting systems are of the shunt-wound type, this arrangement being particularly adapted to the work required, while the series winding is especially adapted for use in the starting motor. Owing to the fact that the shunt generator has the characteristic of increasing its voltage and current output as the speed increases, some auxiliary means must be employed for protecting the generator windings against overload, and the battery against overcharge. This is done by controlling the strength of the field current, which in turn controls the strength of the field magnetism, and the voltage generated.

The strength of the field magnetism may be regulated and controlled in three different ways:

1. By the use of a differential or reverse series field winding in which the series winding opposes the shunt winding.
2. A vibrating relay or regulator which cuts resistance in and out of the field circuit in such a way as to maintain a constant voltage or a constant current.
3. The third brush principle of regulation, which depends upon the reactions that take place in the armature and the resulting distortion of the magnetic field passing through the armature as the generator increases in speed.

Bucking Series Generator.—The reverse-series or bucking-series method of regulating the current output of the generator is perhaps the simplest method in use, as it makes the machine inherently self-regulating with no moving parts and requires no

adjustments due to wear and long usage. A typical example of this method of control is found in the Auto-Lite two-pole generator shown in Fig. 991. This is a differentially compound-wound machine, using the long-shunt field connection. As the voltage of the generator builds up, current flows through the shunt field winding *Sh* and establishes a magnetic flux across the armature. Current also flows from the positive generator brush through the potential winding, *V*, of the cut-out and back to the negative brush through the ground. Both of these circuits lead through the reverse-series field winding *Se* in the direction shown by the arrows. When the speed and voltage of the generator increase to the point where the cut-out contacts are closed, a small charging current will flow from the positive brush of the

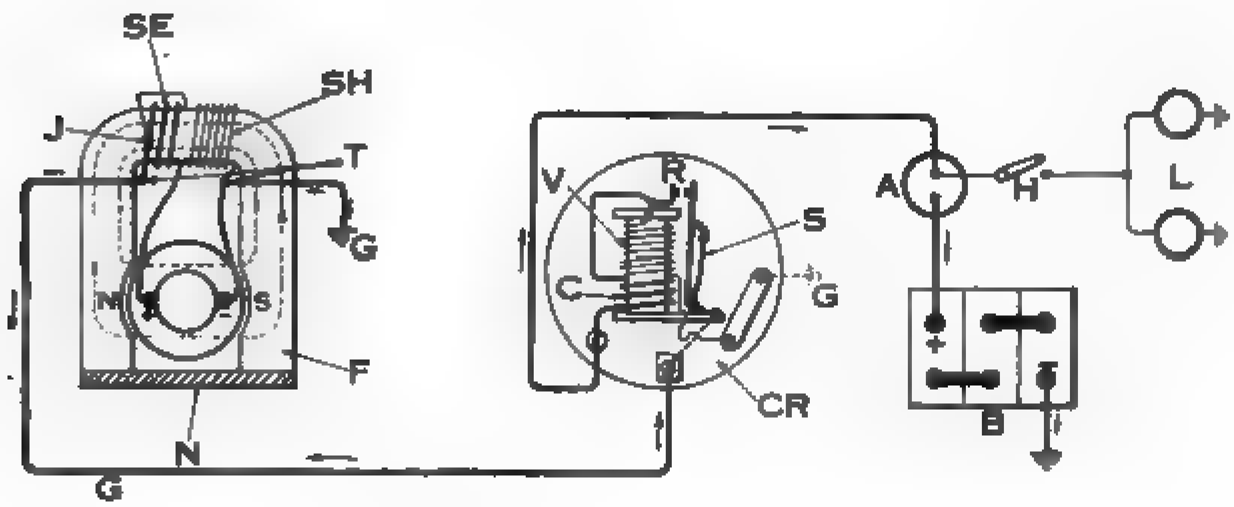


FIG. 991.—Wiring diagram for Auto-Lite, bucking-series, charging generator, reverse-current relay and storage battery.

generator, through the reversed-series field winding, through the cut-out contacts *R* and current coil *C*, through the ammeter *A*, and to the positive terminal of the battery. After passing through the battery it returns through the frame of the car to the negative brush of the generator By inspection of the diagram it will be seen that this current flows through the reverse-series field winding in a direction opposite to that in which the current flows through the shunt-field winding, thereby producing a demagnetizing effect upon the field flux as the generator speed and current output increase. This results in a weakening of the field magnetism as the generator speed increases, so that after the maximum charging current of 10 or 12 amperes is reached the current output of the generator will never exceed this amount no matter how much the speed of the generator may be increased.

Since the current regulation of this type of generator depends upon the charging current flowing through the reverse-series field winding, it is highly important that the charging circuit should never be open circuited at any point, and precaution must be taken to see that the cut-out contacts are maintained in good shape and close properly; that the battery terminals are free from corrosion, and that all connections are maintained mechanically and electrically in good condition. If for any reason an open circuit should occur in the charging line, the regulation of the generator would be destroyed, and the voltage would build up to an excessive value and probably cause serious damage to the armature and field windings, as well as to the windings of the cut-out. The lights will also be burned out if they should be turned on while the car is being operated at a speed in excess of 18 or 20 miles per hour.

If it becomes necessary to operate a car using the reverse-series field method of generator regulation with the storage battery or any other part of the charging circuit removed, or otherwise open circuited, it is absolutely necessary to take the precaution of short-circuiting the generator terminals in order that a current may still flow through the reverse-series field winding and prevent the generator from building up an excessive voltage which would be dangerous to its windings.

It is not practical to change the charging rate of this type of generator, as it would be necessary to alter the number of turns in the reverse-series field coil. Increasing the number of turns in this winding would decrease the charging rate, while decreasing the number of turns in this winding would have the effect of increasing the charging rate. With this type of machine, as with other types of constant current regulating devices, the charging current remains the same under all conditions of charge of the battery; i.e., the battery will receive the same charging current when fully charged as when only partially charged, thus tending to overcharge and overheat the battery when the car is driven on long tours. This is sometimes compensated for by turning on the lamps for sufficient periods to prevent the battery from being overcharged.

Current Regulation by Means of Vibrating Regulator.—In Fig. 992 is shown a circuit diagram of a typical system employing a vibrating regulator or relay for maintaining a **constant current**

output of the generator, which is of the ordinary shunt-wound type. The regulating relay consists of a soft iron core *J*, around which is placed a single winding of heavy wire *V*, similar to the current coil on the cut-out; a set of contacts *P*, normally held closed by a spring *N*, and a small resistance unit *R* connected across the contacts. The winding of the relay is connected in series with the charging circuit so that all current passing through the battery must also pass through this winding.

The regulator controls the current output of the generator under varying conditions of speed, by cutting the resistance unit in and out of the shunt field circuit as the contacts open and close under the varying magnetic pull produced by the core. Referring to Fig. 992, the operation of the regulator is as

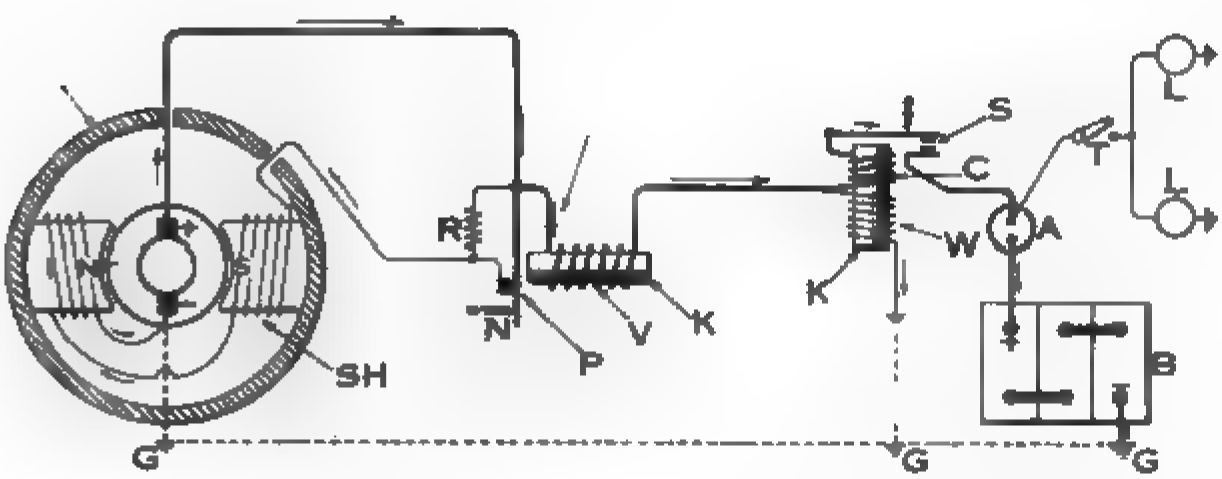


FIG. 992.—Electrical circuits through vibrating regulator designed to maintain a constant current at all times from the generator.

follows: The generator builds up as a simple shunt-wound machine; the path of the field current is from the positive brush of the generator, through the contacts of the regulating relay, through the field winding, and back to the negative brush of the generator. As the speed and generated voltage of the generator increase, the cut-out contacts *S* will close, and the charging current will flow through the winding of the regulating relay. As the speed increases the charging current will increase until it reaches the maximum value for which the regulator has been adjusted, which is about 12 or 15 amperes; the core of the relay will now be magnetized sufficiently to attract the armature carrying the movable contact, and the contacts will open against the tension of the spring *N*, inserting the resistance unit *R* in the shunt-field circuit, causing the field current to be lessened.

This weakens the strength of the magnetic field and reduces the generated voltage, which in turn causes the charging current to decrease. When the charging current has reduced 0.5 to 1.5 amperes below the point at which the contacts open, the magnetic effect produced by it in the core is not sufficient to hold the contacts open against the tension of the spring, and they will close, short-circuiting the resistance unit, thus restoring the full field strength and causing the charging current to again increase. Under actual operating conditions the contacts open and close very rapidly; thus the charging current is continually changing, but within a very small range of perhaps a fraction of an ampere, thus preventing the charging current from ever exceeding the maximum rate for which the relay is adjusted, no matter how high the speed of the car may be.

The maximum charging rate of a system employing current regulation by a vibrating relay may be increased by increasing the tension of the spring on the relay contacts, or decreased by decreasing the tension of the spring. In case the charging rate is increased, care must be taken to see that the generator windings are not being overloaded.

As in the bucking-series method of regulation, it is highly important that an open circuit should never occur in the charging line, as the regulation of the system would thereby be destroyed and serious damage to the windings of the generator and relay regulator would result. Should it become necessary to operate a car equipped with a regulator of this type, with the storage battery or any other part of the charging circuit removed, the precaution must first be taken to open-circuit the field winding of the generator, thereby preventing it from building up; or to short-circuit the wires leading to the battery, thus preventing the current from ever exceeding the maximum value for which the regulating relay has been adjusted.

This method of current regulation is being used on some cars equipped with Remy starting and lighting systems.

Voltage Regulation by Means of Vibrating Regulator.—In Fig. 993 is shown a typical starting and lighting system employing a vibrating type of regulator for maintaining the voltage of the generator at a constant value. The construction of the regulator is very similar to that used to obtain constant current regulation, with the exception that the current winding of heavy wire is

replaced with a potential coil, *V*, consisting of a large number of turns of fine wire similar to the one used for the potential winding on the reverse current cut-out. This potential winding is connected across the brushes of the generator in parallel with the battery instead of in series with it as in the constant current regulator. The current which flows through this potential coil and the amount of magnetic pull produced by the core on the contacts depend upon the voltage developed by the generator. As the generator speeds up to the point where the voltage exceeds the value for which the regulator has been adjusted, which is 7.75 volts on a 6-volt system, a larger current will be forced through the potential winding of the relay by the increased voltage, causing the magnetic pull of the core to increase to such

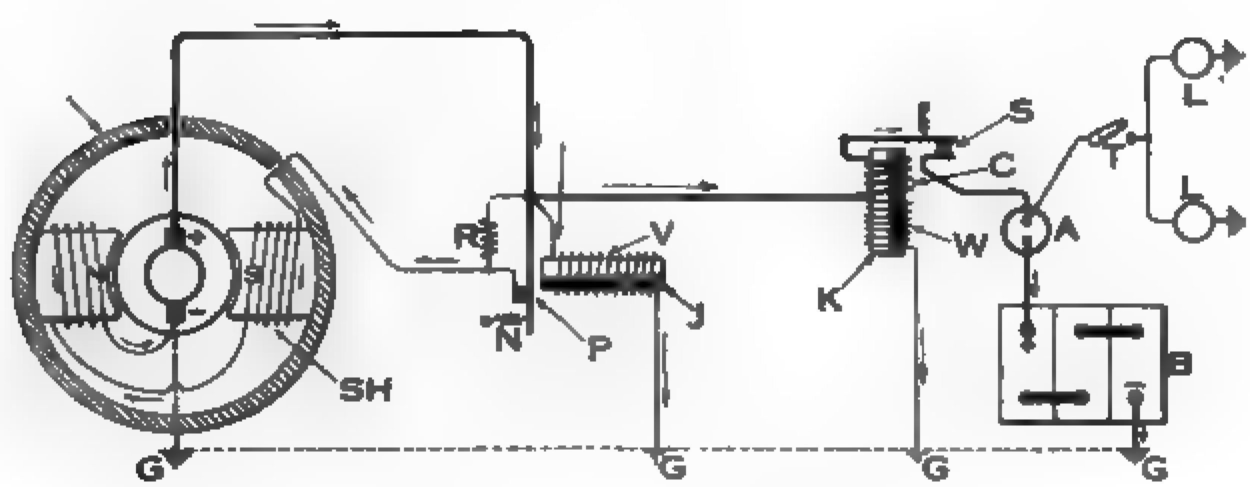


Fig. 993.—Electrical circuits through vibrating regulator designed to maintain a constant-voltage output from the generator.

an extent that the spring tension will be overcome and the contacts opened, thereby inserting the resistance unit in the shunt-field circuit. This added resistance reduces the shunt-field current and lowers the generated voltage. As soon as the terminal voltage falls slightly below 7.75 volts, the current in the potential coil decreases to a value where it does not produce sufficient magnetic pull to hold the contacts open against the tension of the spring, and they will therefore close, short-circuiting the resistance unit, thus restoring the field current to its full value, and the voltage of the generator begins to rise. This cycle of operations is repeated very rapidly, and the contacts open and close with such rapidity that the voltage is held practically constant at 7.75 volts at all speeds above the critical speed at which this voltage is generated with the resistance unit cutout of circuit.

With generators employing constant voltage regulation the amount of current delivered by the generator depends upon the condition of charge of the storage battery and the amount of current being used for lamps or other devices, while the voltage remains practically constant at all loads after the speed has reached the point where the critical pressure of 7.75 volts is generated.

The voltage of a storage battery depends upon the condition of its charge, being higher for a fully charged battery than for a partially or completely discharged one, and since the voltage available for sending current through the battery is the difference between the voltage of the generator and that of the battery, it will be seen that the charging current that passes through the battery will vary with the condition of its charge, being a maximum when the battery is in a discharged condition. As the charge proceeds the voltage of the battery rises, so that the difference between the voltage of the generator and the voltage of the battery decreases until at the completion of the charge this difference is very slight, and only a very small charging current will flow. The charging current, which is variable and independent of the speed, varies from 15 to 20 amperes with a discharged battery to about 5 amperes for a fully charged battery. The tapered charge thus given the battery is the ideal one, charging it in the minimum possible time and without the danger of overcharging after the normal charge has been completed, as is often the case with the constant-current system of regulation.

The voltage maintained by the generator, and consequently the charging current passing through the battery, may be increased on this type of system by increasing the tension of the spring on the relay; but if the voltage is raised above 7.75 volts an excessive charging current will result, which may overload the generator and overcharge the battery. The life of the lamps will also be shortened if the voltage is maintained above this value.

Since the regulation of this type of system does not depend upon the charging current itself, the car may be operated at speeds below 30 M. P. H. without the storage battery being in the charging circuit, with no danger of damaging the generator windings or burning out the lamps, as the voltage will still be maintained at the same constant value.

Third-Brush Regulation.—The third-brush principle of reg-

ulating the current output of the generator depends for its operation entirely upon the reactions which exist in the armature when its windings are carrying current. Fig. 994 shows the circuit diagram of a typical generator employing the third-brush principle of current regulation. *A* and *B* are the main generator brushes connected to the charging circuit, and *C* is the auxiliary or third brush which connects to one end of the shunt-field winding. The other end of the field winding is connected to brush *B*, so that the generator is primarily a shunt machine. The auxiliary brush is positive with respect to brush *B*, and there-

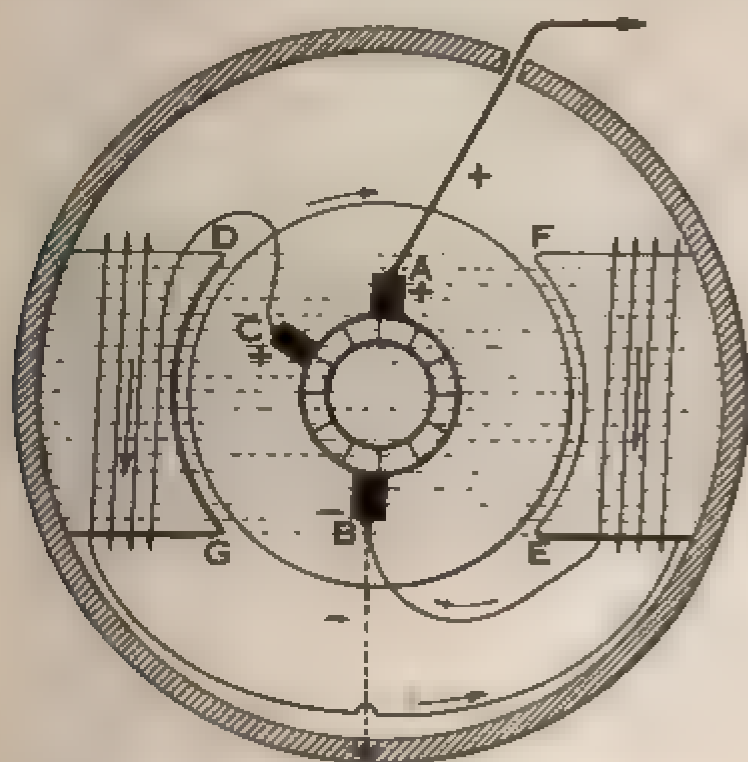


Fig. 994.—"Third-brush" generator with no load and undistorted field.

fore current flows from *C* through the shunt-field winding and into brush *B*.

When the generator is running at a low speed and little or no current is flowing through the armature winding, the magnetic flux produced by the field will be practically straight through the armature from pole to pole as shown, and the voltage generated by each armature coil within this field is practically uniform. On a generator of the 6-volt type, in which the terminal voltage is approximately 7.75 volts, the third brush is placed in such a position on the commutator that about 5 volts will be impressed on the shunt field, forcing a current of about 1.25 amperes through the field winding.

As the speed of the generator increases, the voltage and the current flowing through the armature winding will be increased. This increased armature current tends to produce a cross magneting field in a direction at right angles to the main field which distorts the magnetic field produced by the shunt-field winding, so that instead of the flux being equally distributed over the pole faces and passing straight through the armature as in Fig. 994, it is now distorted as shown in Fig. 995. The field flux now becomes much denser at the trailing pole tips *D* and *E* and less dense at the leading pole tips *F* and *G*, and the armature coils no

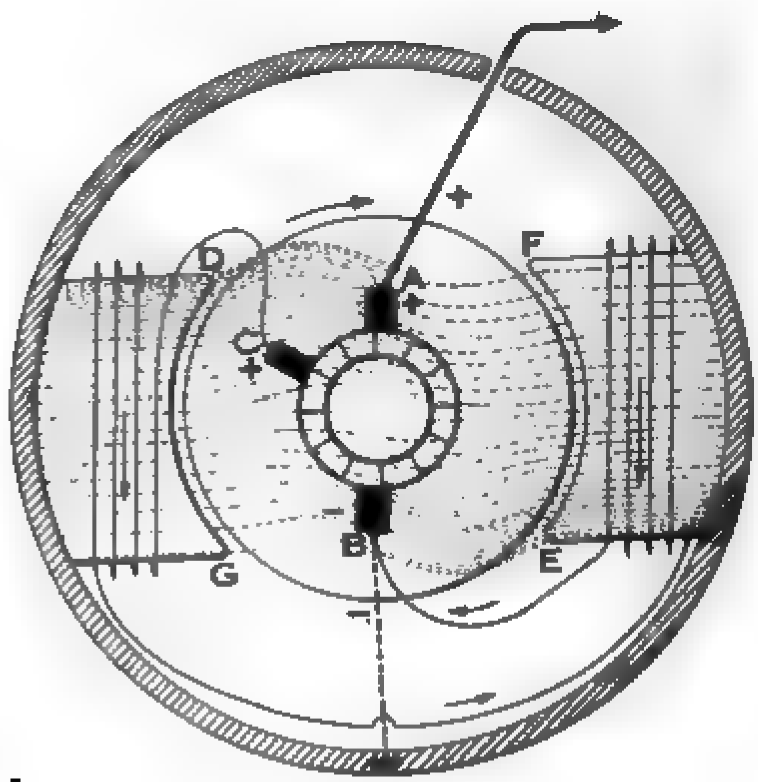


FIG. 995.—"Third-brush" generator carrying normal load showing distortion of magnetic field

longer generate a uniform voltage. Although the total voltage generated remains nearly the same, the greater part of the voltage will now be generated by the coils connected to the commutator between the brushes *C* and *A*, since these coils are cutting through a much denser magnetic field than those connected to the commutator between the brushes *C* and *B*; therefore the voltage generated between the brushes *C* and *B* will decrease as the speed increases. Since the voltage applied to the shunt-field winding is the same as that between the brushes *C* and *B*, less current will be forced through the field winding and the total amount of field magnetism will be reduced. This will have the

effect of lowering the generated voltage and the charging current flowing through the armature. The reaction produced by this current will thus be lessened and the field flux will tend to return to its original value; but any increase in the field magnetism will be accompanied by an increase in the charging current flowing through the armature, which will again react upon the field, distorting it, thus automatically regulating the charging current as the speed varies.

One of the advantages of the third-brush method of regulation is that the charging current will gradually increase with the speed until the maximum value for which the generator has been adjusted has been reached, which occurs at a car speed of about 25 miles per hour; above this speed, the charging current will begin to decrease, until at 40 or 45 miles per hour the charging rate has decreased to one-half of its maximum value. This is due to the fact that at high speeds a given armature current will produce a greater distortion of the field than at a lower speed, because the field flux will be weaker in proportion to the armature current. This is an advantage, as the maximum charging current will be obtained at normal driving speeds, while for long drives at a higher speed, when the starter and lights are used comparatively little, the decreased charging rate tends to prevent overheating of the generator and overcharging of the battery.

Another advantage of the third-brush system of regulation is the ease with which the charging rate may be adjusted to suit the conditions under which the system is operating. The charging current may be varied by changing the position of the third brush on the commutator, and most manufacturers make provision for doing this by mounting the brush on a sliding or adjustable brush holder. Referring to Fig. 994, it will be seen that shifting the position of this brush in the direction in which the armature rotates will have the effect of raising the voltage applied to the shunt-field winding and therefore increasing the generated voltage and charging current, while moving it in the opposite direction will have the effect of decreasing the charging current. If the position of the brush is changed, care should be taken to properly reseat it on the commutator, thus insuring a low contact resistance.

As in the methods previously described for obtaining current

regulation, it is of the utmost importance that all connections at the battery terminals and elsewhere in the charging circuit should be frequently inspected to make sure they are tight and in good condition, as an open circuit in the charging circuit will be almost sure to burn out the armature winding of the generator, due to the excessive rise in voltage and current.

In case a car equipped with the third-brush system of current control is to be operated with the battery or other part of the charging circuit removed, the precaution must first be taken to open the shunt-field circuit or short-circuit the terminals of the generator to prevent it from building up.

The Remy Two-Unit System with Third-Brush Regulation and Thermostatic Control

The Remy starting and lighting system shown in Fig. 997 is used on the Oakland, Model 34, and other cars, and represents the generating portion of a typical two-unit system of the single-wire ground return type. The generator is a 6-volt, two-pole machine in which the current is regulated by the third-brush method, supplemented by the Remy thermostatic control. Fig. 996 shows the construction of the thermostat, which is mounted inside of the generator housing just over the commutator. It consists of a stamped steel bracket carrying a resistance unit connected to a therom blade, carrying one of two silver contacts at its free end. The thermo blade consists of a strip of nickel steel, welded to a strip of spring brass. When heated, the brass strip expands at a faster rate than the strip of nickel steel and causes the free end of the blade to warp as shown. The stationary contact is adjustable, but, after once being adjusted at the factory, is fastened in place by being soldered and will probably never require further attention. At temperatures below 175° F. the spring tension of the blade holds the contacts firmly together, thus short-circuiting the resistance unit which is connected across them; but at temperatures above 175° the heat causes the metals of the blade to expand unequally, and as a result it bends in such a way as to separate the contacts, thus inserting the resistance unit R in series with the shunt field and reducing the field current, which in turn has the effect of decreasing the charging current (see Fig. 997). Under actual operating conditions the generator will charge the battery at the normally high charging rate until the

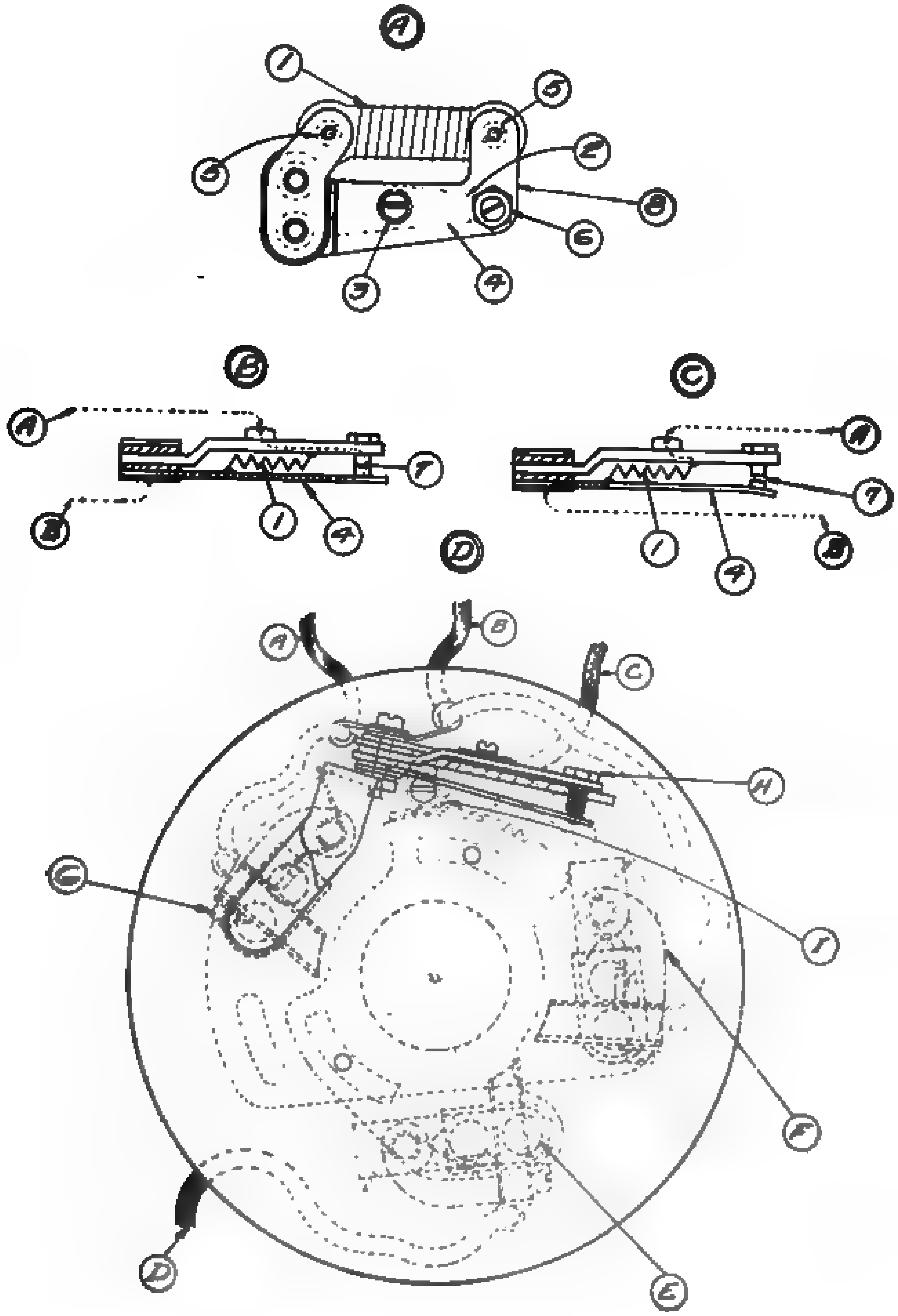


Fig. 996.—Detailed construction of thermostat for field control of Remy generator.

generator and battery begin to heat up. When the given temperature has been reached the thermostat contacts will be opened, and the added resistance thus inserted in the field circuit will cause the charging current to drop to about two-thirds of its original value.

The advantage of the thermostat control is that it gives a higher charging rate in winter, when the efficiency of the battery

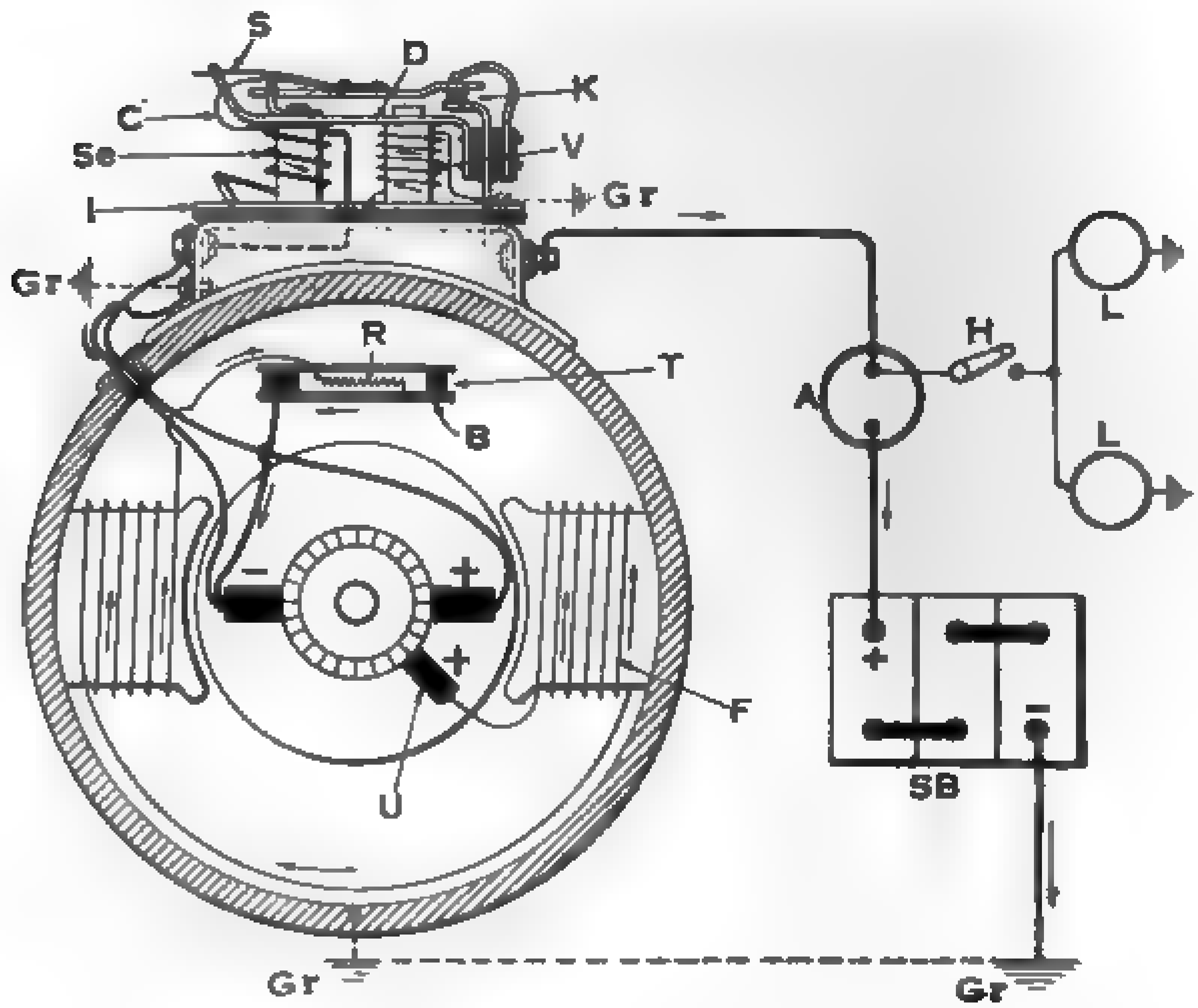


FIG. 997.—Wiring diagram for electrical circuits of model 234-A Remy generator with thermostatic control, shown at *T* and reverse current cutout mounted on top of generator.

is low, and is severely taxed by the increased demand for current by the starting and lighting system. It also gives a higher charging rate when the car is driven at slow speeds, and for short distances between stops In warm weather it prevents the battery from being overcharged by reducing the charging rate as soon as the generator warms up.

The Northeast Equipment for Dodge Car

The Northeast starting and lighting system used on the later models of the Dodge car is a single-unit, 12-volt system. It

consists primarily of the Northeast, Model G motor-generator, combined starting switch and reverse-current cut-out, storage battery, and current indicator.

A circuit diagram of this system is shown in Fig. 998. When the starting pedal is depressed, the starting switch is closed, thus short-circuiting the terminals of the cut-out This allows

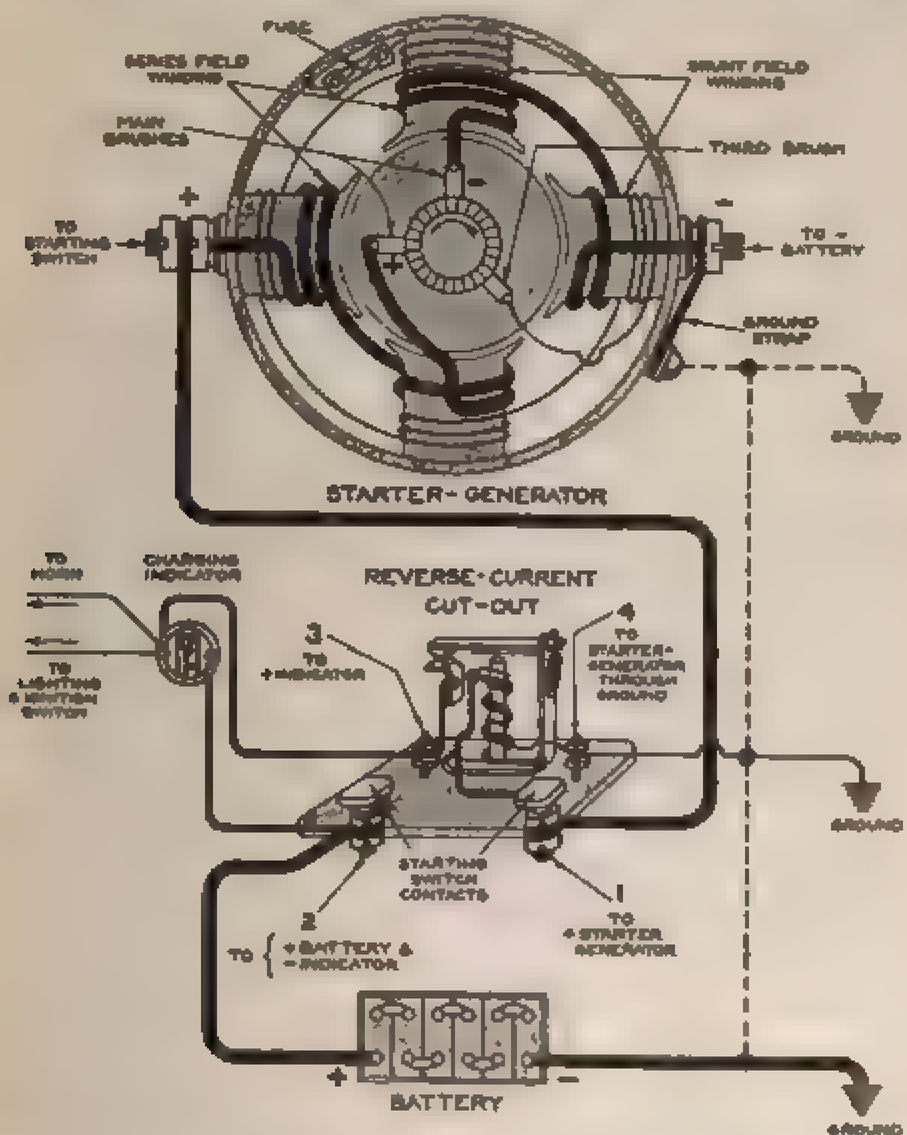


FIG. 998. -Wiring diagram of Northeast single-unit motor-generator, reverse current cutout and 12 volt storage battery, as applied to Dodge automobiles

current to flow from the positive terminal of the battery, through the starting switch and windings of the motor-generator, and then back to the negative terminal of the battery The motor-generator thus operates as a motor and turns the engine crank shaft. After the engine begins firing and speeds up, the motor-generator is automatically converted into a generator and begins charging the battery. The path of the current through

the charging circuit is the same as through the starting circuit, except at the starting switch, where instead of passing from one terminal of the switch contacts to the other, through the switch blade, as when the switch is closed, it now flows through the current winding of the reverse-current cut-out and current indicator. The current indicator is of the C. O. D. type, indicating "Charge," "Off," and "Discharge," depending upon whether the battery is being charged or discharged. The motor-generator is driven at three times crank-shaft speed by a silent chain running in oil. It is a compound-wound machine of the true single-unit type, employing the same field and armature windings to perform both the generator and motor functions.

When operating as a starting motor the machine operates as a cumulative compound machine, thus giving a high starting torque; but when driven as a generator it operates as a differentially compound machine, and the charging current is regulated by the differential action of the series field upon the shunt field, in connection with the third-brush principle of current regulation.

The generator begins to charge the battery at about 10 miles per hour, and the charging rate steadily increases until it reaches its maximum value of about 6 amperes at 16 or 17 miles per hour. From 16 to 21 miles per hour the charging rate remains approximately the same, but at higher speeds the charging rate decreases until it may be only about one-third of its maximum value.

The shunt field is provided with a protective fuse, and this should be removed in case the car is to be operated with the battery removed.

Provision is made for readily changing the charging rate by changing the position of the third brush, but under normal operating conditions the maximum charging rate should not be more than about 6 amperes.

The "Liberty" Ford Starting and Lighting System

The starting and lighting equipment now furnished with the Ford car is a typical two-unit, 6-volt, single-wire system. The starting motor is a four-pole, series-wound machine using the Bendix drive which meshes with the gear teeth on the fly-wheel.

The generator is of the four-pole type, using the third-brush method of current regulation. It is driven by a pinion mounted on one end of the armature shaft, which meshes with one of the

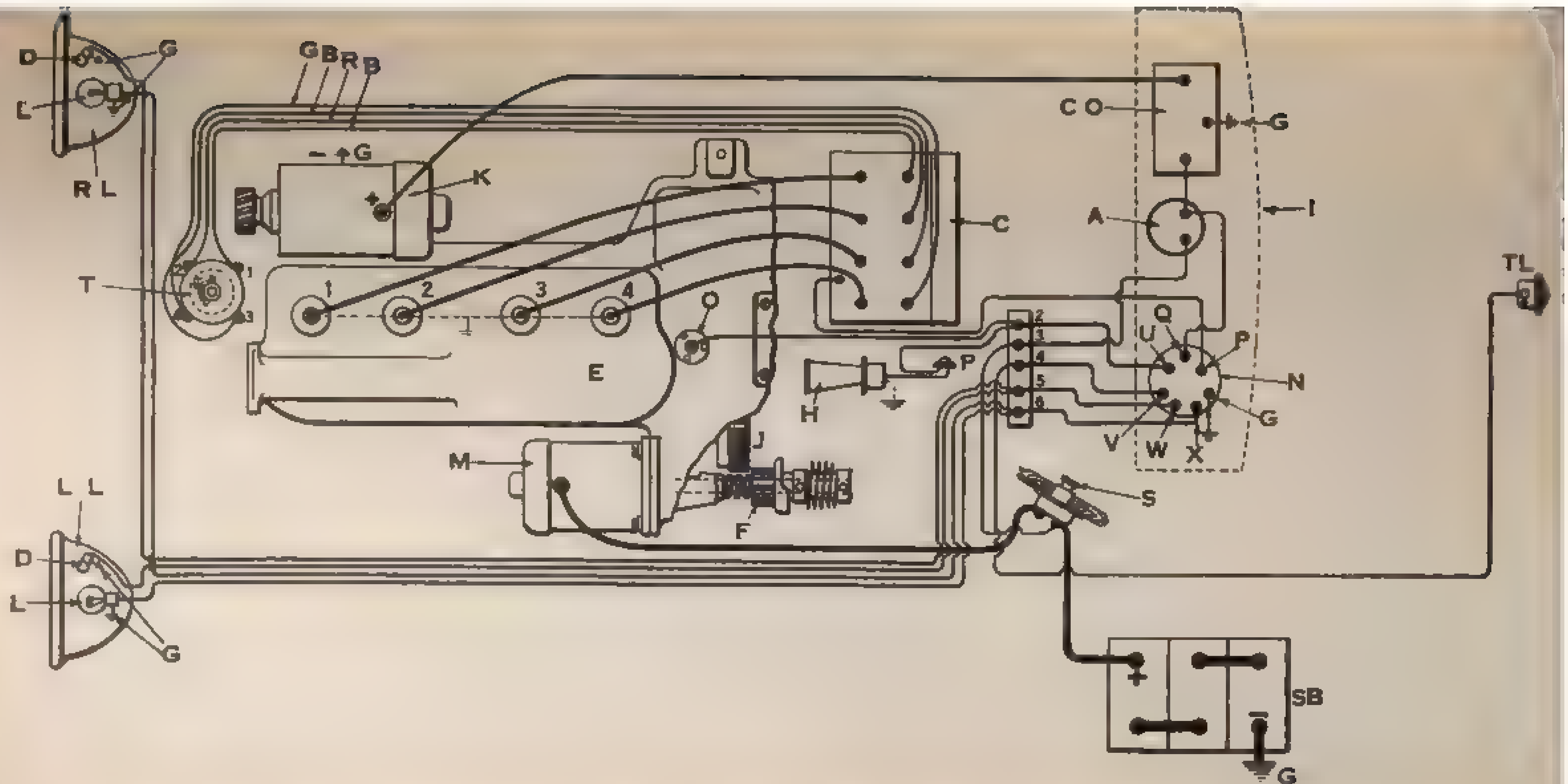


Fig. 999.—General layout of electrical circuits, "Liberty" charging generator, starting motor, and ignition and lighting circuits on Ford automobile.

timing gears. The contacts of the reverse current cut-out, which is mounted on top of the generator, are adjusted so as to close at a car speed of about 10 miles per hour, and the maximum charging rate is reached at a speed of about 20 miles per hour, above which the charging rate decreases, a characteristic of the third-brush generator.

Fig. 999 shows the wiring diagram for the complete starting, lighting and ignition system. Dimming of the headlights on this system is accomplished by using lamps of the double-filament type, one filament being smaller than the other and slightly out of focus. Fig. 1000 gives a general view of the electrical equipment on a Ford car, showing the actual location of the various apparatus.

The Delco Single-Unit Starting and Lighting System

The Delco single-unit starting and lighting system used on the Buick, Model 46, is typical of the 6-volt, single-unit Delco system installed on many high-grade cars. It consists essentially of the Delco motor-generator, combination lighting and ignition switch, and storage battery.

The armature of the motor-generator is driven through an overrunning clutch from an extension of the pump shaft when the machine is driven by the engine, and operates as a generator charging the battery. As shown in Fig. 1001, a small pinion is mounted on the rear end of the armature shaft and meshes with an intermediate gear, which in turn meshes with the teeth on the fly-wheel for cranking the engine when the unit operates as a motor. As previously explained, one of the intermediate gears contains an overrunning clutch to prevent the fly-wheel from driving the armature at an excessive speed when the engine starts firing. The Delco motor-generator differs from the usual machine of this type in that it has individual windings on the armature and field for performing the generator and motor functions. The armature windings are connected to separate commutators, having two separate sets of brushes. One of the field windings is a shunt winding and is used when the machine operates as a generator, while the other is a series winding and is used only when the machine operates as a motor for cranking rposes. The brush mechanism is constructed in such a way , when the starting pedal is depressed for cranking the

engine, both motor brushes, one of which is normally out of contact with the commutator, will be brought into contact with the commutator connected to the series motor winding, while at

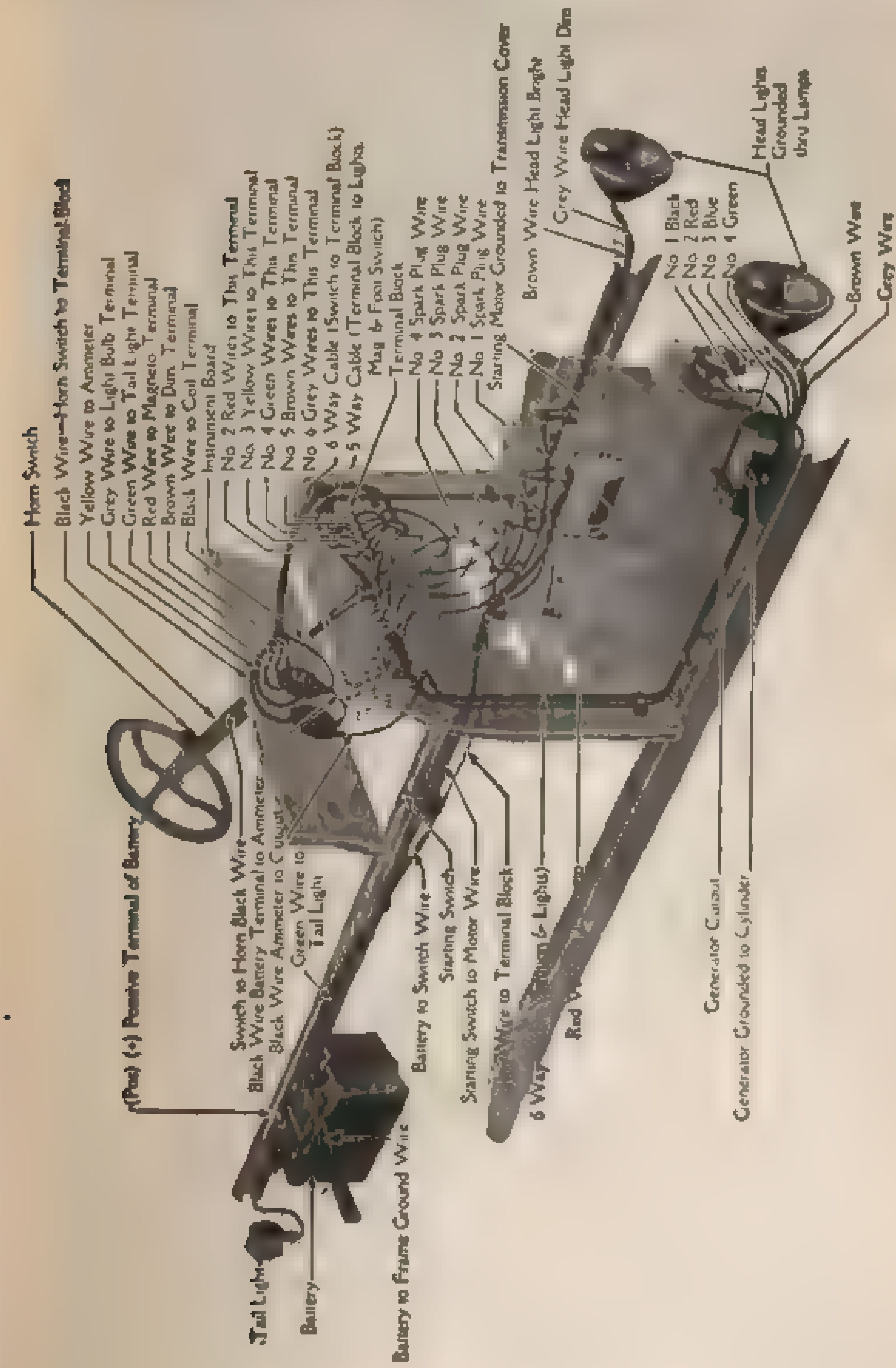
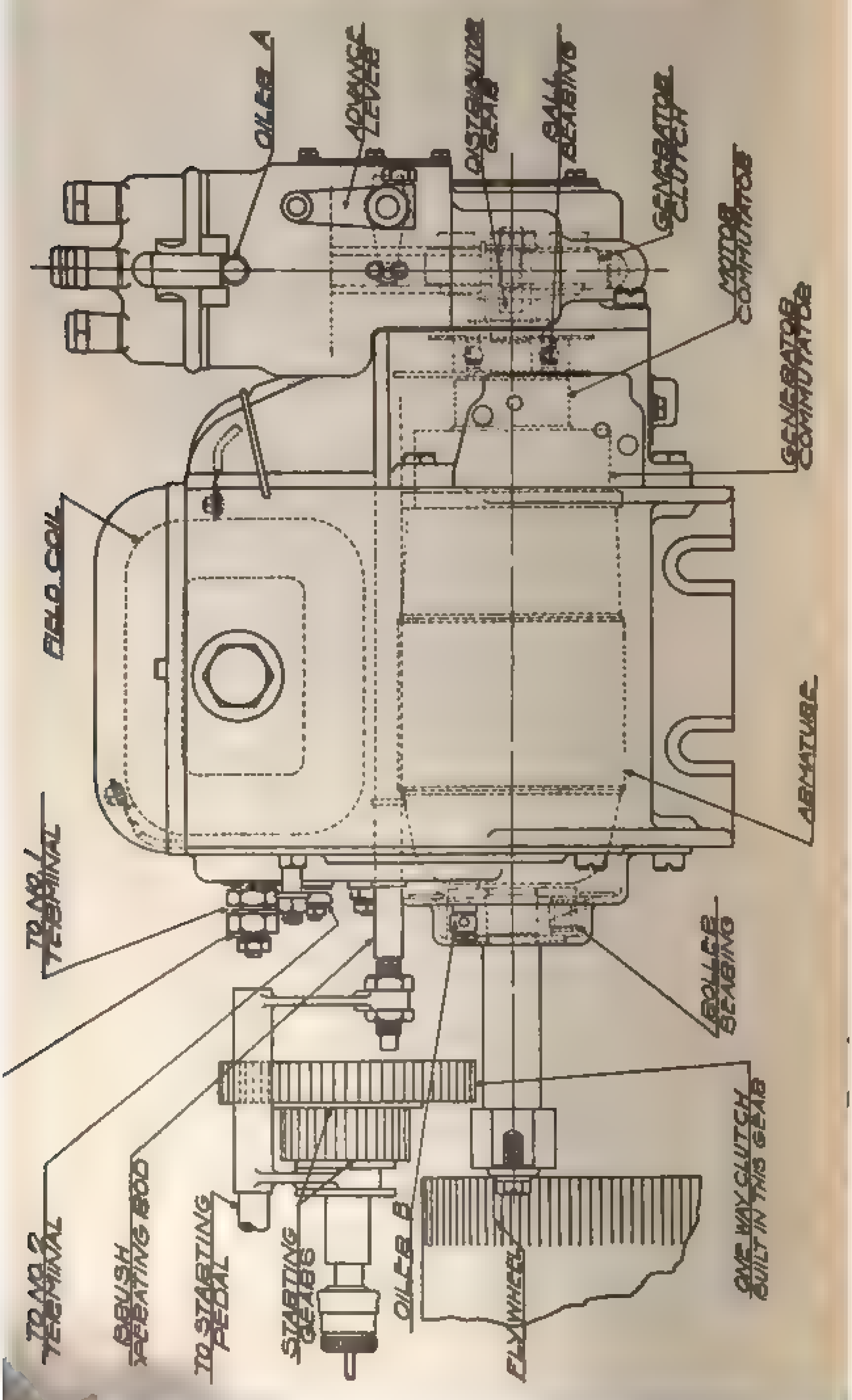


FIG. 1000


OILER A
ADVANCE LEVER
DISTRIBUTOR GEAR
BALL BEARING
GENERATOR CLUTCH
MOTOR COMMUTATOR
GENERATOR COMMUTATOR
FIELD COIL
ARMATURE
TO NO. 1 TERMINAL
ROLLER BEARING
TO NO. 2 TERMINAL
BRUSH
TO STARTING PEDAL
STARTING GEARS
OILER B
FLYWHEEL
ONE WAY CLUTCH BUILT IN THIS GEAR

the same time one of the generator brushes is lifted from its commutator, thus opening the generator circuit while the cranking operation is being performed. When the starting pedal is released, one of the starting brushes is automatically raised and the generator brush is dropped to its former place on the commutator, thus completing the generator circuit for charging the battery.

Fig. 1002 is a complete circuit diagram for this system. It will be seen that the button on the left of the combination switch controls the ignition circuit and also the charging circuit between the generator and storage battery. The second button controls

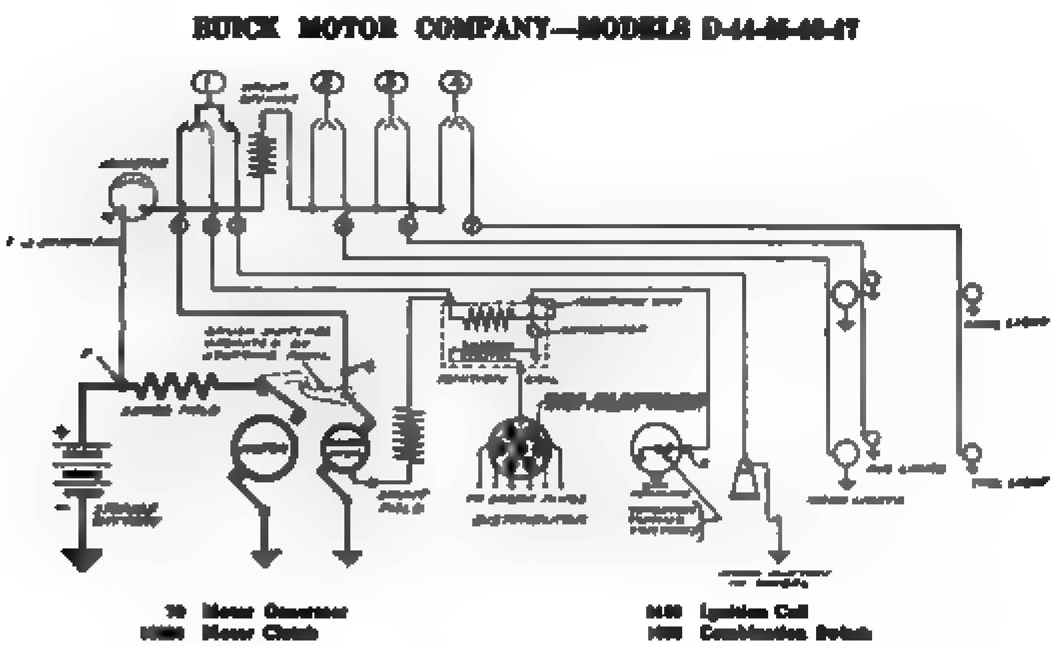


FIG. 1002.—Wiring circuits for Delco starter-generator equipment for Buick automobile, including circuit breaker and lighting circuits.

the head lights, and the third button controls the auxiliary or "dim" lights, while the fourth button controls the cowl and tail lights.

Fig. 1002 also shows the winding and contacts of the circuit-breaker which is mounted on the back of the combination switch and connected in series with the light circuits. It takes the place of fuses, which are often used for protecting the battery against excessive discharge in case a ground should occur on any of the light circuits. In case a ground should occur on any of these circuits, an excessive current will flow through the windings of the circuit-breaker, causing it to open the contacts intermittently, making a clicking sound, but automatically restoring

the contacts to the closed position when the ground or short circuit is removed.

The motor-generator has three separate operations to perform: (1) motoring the generator, (2) cranking the engine, and (3) generating electrical energy.

When the ignition switch is closed, the circuit between the battery and generator will be completed and current will flow from the battery, causing the armature to slowly turn, thus motoring the generator so that the starting gears may be easily brought into mesh when the starting pedal is depressed. Failure of the machine to operate as a motor may be due to a dirty commutator and poor brush contact; an open circuit in the shunt field or armature winding, or a weak battery or sticking generator brush.

The first part of the movement of the starting pedal shifts the starter gears into mesh between the fly-wheel and the pinion on the armature shaft. The gears should not be forced together in case they do not mesh readily, but the starting pedal should be slightly released, thus allowing the armature to rotate and change the position of the gear teeth. As the starting pedal is moved farther, the brush switching mechanism is operated in such a way as to raise one of the generator brushes, thus opening the generator circuit and preventing the generator windings and motor windings from opposing each other during the cranking operating, as this would cause a very slow cranking speed.

On some cars equipped with this system the generator brush is not raised, but the generator circuit is opened by a switch which is located in the back of the motor-generator and operated by the shifting mechanism.

The last part of the movement of the starter pedal operates the motor brush, bringing it into contact with the motor commutator, thus completing the circuit between the storage battery and motor windings, and the machine now operates as a motor, cranking the engine. Upon releasing the starting pedal the above operations are reversed, leaving the generator windings in circuit for the generation of current.

The armature is now driven through the overrunning clutch and begins to charge the battery at a car speed of about 7 miles per hour. The current output of the generator is regulated by the third-brush principle, and the charging current will increase

to about 15 amperes at a speed of 25 miles per hour, above which it will decrease slightly.

The ammeter is connected as shown in Fig. 1002 and indicates all current flowing into or out of the storage battery, except that used for starting purposes.

By inspection of the diagram it will be seen that the shunt field is not connected directly between the third brush and the main brush of opposite polarity, as is usually the case, but one end of the winding is taken out through the generator housing and connected on to the terminal of the ignition coil as shown. The path of the shunt field current is now as follows: From the third brush, through the field winding and then through the contacts of the combination switch which control the ignition and charging current, and then back to the main generator brush of opposite polarity. The shunt-field winding is connected through the combination switch, so that in case the engine ignition is turned off when coasting down long grades the shunt-field circuit will also be opened and thus prevent the generator from building up. If the generator was permitted to build up when the ignition switch was turned off, thus opening the charging circuit, the windings of the generator might be seriously damaged.

In this system, dimming of the headlights is accomplished by providing an auxiliary set of lamps of low candle power, but where desired the dimming may be accomplished by inserting a resistance unit in series with the headlamps.

SECTION XVIII CHAPTER IV

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

STARTING AND LIGHTING SYSTEMS

1. Explain the general scheme of the single-unit electric starting system.
2. Explain the general plan of the two-unit electric starting system.
3. What are the relative advantages of the two systems and under what circumstances is one to be preferred over the other?
4. Explain the "sliding pinion" type of drive for connecting the starting motor to the engine for cranking.

5. Explain "magnetic" type of drive for connecting the starting motor to engine when cranking.

6. Explain the "Bendix" drive for connecting the starting motor to engine when cranking.

7. What are the particular advantages of each of the three types?

8. Explain the object and principle of operation of the "reverse-current cutout" used in connection with the charging generator and storage battery on a starting system. Sketch.

9. Give a diagrammatical sketch of a "single-unit" starting system complete. Mark the name of each part.

10. Give a diagrammatical sketch of a "two-unit" starting system complete.

11. Explain the construction and principle of operation of the "bucking series" type of charging generator for automobile work. Sketch.

12. Explain the construction and principle of operation of the "vibrating relay" type of regulator for delivering a constant current from a variable speed generator. Sketch.

13. Explain the construction and principle of operation of the "vibrating relay" type of regulator for delivering a constant potential from a variable speed generator. Sketch.

14. Explain the construction and principle of operation of the "third-brush" type of generator for delivering a constant output at variable speed. Sketch.

15. Sketch and explain the general plan of the Remy two-unit starting system with third-brush generator and thermostatic control. What are its advantages?

16. Sketch and explain the general plan of the Northeast single-unit starting system used on Dodge cars.

17. Explain the general plan of the "Liberty" two-unit starting system used on Ford cars.

18. Explain the general plan and details of construction of the "Delco" single-unit starting system. What are its advantages and disadvantages?

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

TRAIN LIGHTING

The majority of first-class passenger coaches, as well as all Pullman cars on all steam passenger lines today, are electrically lighted. The advantages of electricity for this purpose over oil and gas are sufficiently well understood. The essential condition to be met is, that the voltage of the lamps shall be constant at all times, regardless of the number of lamps in use and the speed and the direction of the train.

Three principal systems are in use today

First: The straight storage system, in which each car is supplied with a storage battery of its own.

Second: The head-end system, in which a constant potential generator driven by a direct-connected steam turbine is placed in the baggage car or on the locomotive itself and furnishes current for the whole train.

Third: The axle generator system, in which a small generator mounted under each car is directly driven by a belt from the car axle.

The **straight storage system** was used in the first installations of electric lights on steam cars. It ordinarily consists of thirty-two cells of lead storage battery of about 300 ampere-hours capacity placed in lead-lined compartments supported under the center of the car. The size of the battery is such that it is not practical to exchange a discharged battery for one freshly charged at the end of the line. Therefore the cars must lie over long enough to have the batteries charged. Because of the wide change of temperature the battery varies greatly in capacity, and in extremely cold weather it is sometimes difficult to get enough energy from the battery to care for the lighting throughout a long trip. If the batteries are not placed on charge promptly at the end of a run or are left in a discharged condition, sulphation, with consequent deterioration of the entire battery, results. Furthermore, the change in voltage between the condition of charge and discharge makes an objectionable change in the candle power of the lamps.

In the **head-end system,** a compound-wound generator is driven by a steam turbine, which takes steam from the locomotive. The unit may be mounted in the corner of the baggage car or on the locomotive itself. The complete equipment must include storage batteries, preferably one for each car, to operate the lights when the train is disconnected. This system is used on the Chicago, Milwaukee & St. Paul; the Union Pacific, Chicago, Burlington and Quincy, and the Northern Pacific. It is especially adapted for lights where the runs are exceptionally long. The Baltimore & Ohio also uses the head-end system on a few of its trains.

On the Baltimore & Ohio, the head-end system involves a 20-k.w., 110-volt, compound generator driven by a Curtis turbine at

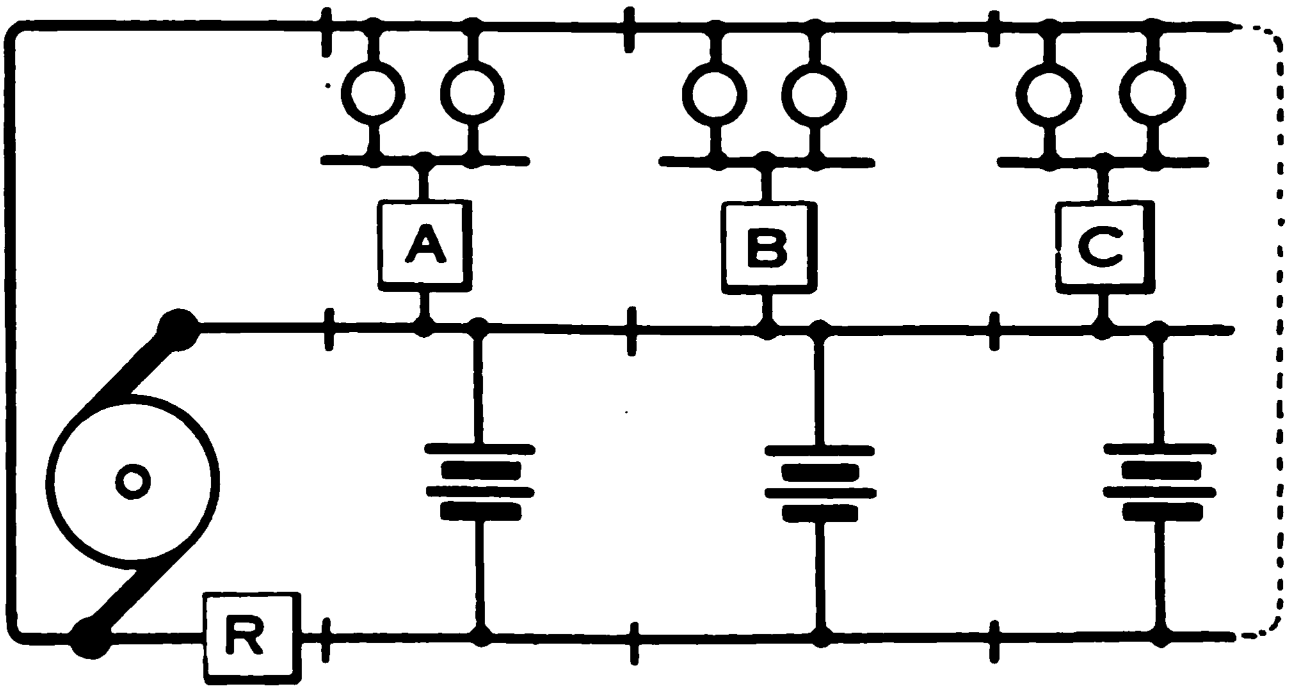


FIG. 1003.—General scheme of Baltimore & Ohio Railroad head-end system of train lighting.

a speed of 4,500 r.p.m., with a pressure of 80 pounds. The Pullman cars on the train each carry a 32-cell, 300-ampere-hour storage battery. Coaches and express cars have no battery. The generator delivers a pressure of from 65 to 90 volts according to the condition of the batteries. When the generator is in operation at the same time that lights are burning, the charging voltage is reduced by means of the regulator, *R*, Fig. 1003, to the amount necessary to merely float the batteries, thus allowing the lamps to be carried directly on the generator and at the same time preventing excessive charging of the batteries. To maintain the lamps at proper voltage, each car is provided with an automatic lamp regulator, *A*, *B*, *C*, Fig. 1003, similar to that shown at *C*, *T*, *K*, *S*, in Fig. 1004, which will be explained later.

This regulator holds the pressure very close to 63 volts, and Tungsten Mazda lamps of this rating are employed. They use a three-wire train line.

The Chicago, Milwaukee & St. Paul also employs a three-wire train line on their head-end system, but arranged so as to give two separate circuits, Fig. 1005. The batteries are connected on one circuit and the lamps on the other. The batteries may thus be charged over one circuit from the generator and the lamps supplied over the other. Or, if the train is broken up or the generator disconnected, the lamps may be thrown directly upon the batteries by connection shown by dotted line. While the generator is operating, however, a variable resistance, *E*, is inserted

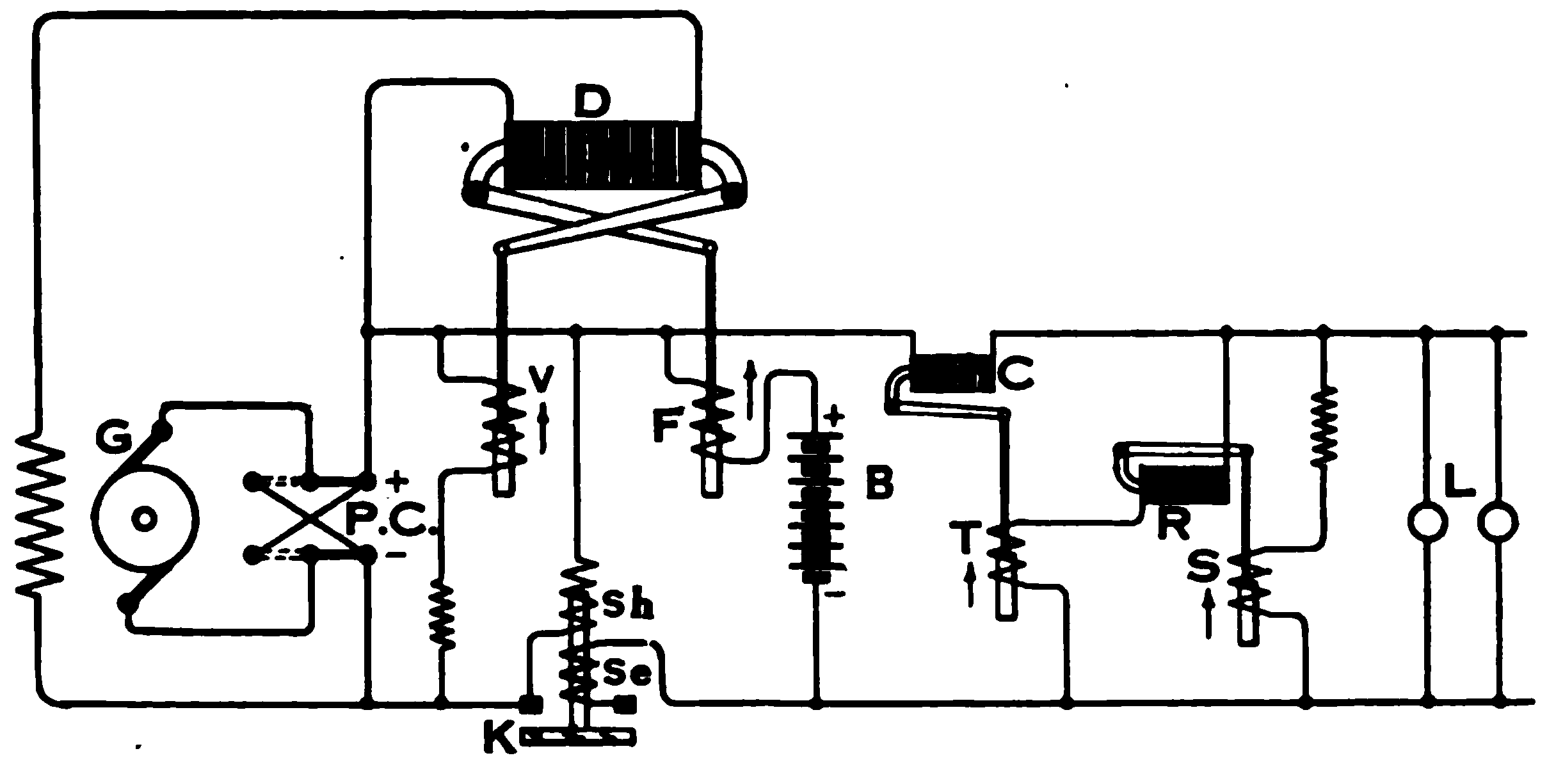


FIG. 1004.—Lamp regulator and battery charging regulator for axle-generator system of train lighting.

in the lamp circuit at the head of the train by means of which the lamp voltage may be maintained constant while the charging current can be altered by a regulator *R*, so as to charge the battery at any desired rate.

In the first attempts at lighting by the head-end system, the generator was allowed to carry the entire lighting load and no storage battery was employed. This naturally resulted in frequent lighting failures due to separating the train or disconnecting the locomotive. It therefore became necessary to use storage batteries to a limited extent. Batteries were first placed on the front and rear cars of the train. Even this was not satisfactory, and head-end systems today generally employ a battery

The head-end systems are standardized at 62 volts, using 32 lead cells in series. This necessitates a pressure of at least 84 volts from the generator to properly charge the battery. The lamp circuit is maintained by the regulators at about 63 volts.

The most expensive system from the standpoint of first cost is the **axle-generator system.** But because of the entire independence of each car and many improvements introduced in recent years, it has come into quite universal use on eastern roads, among which are the Pennsylvania, Baltimore & Ohio, and Southern. In this system a small generator, fully enclosed to exclude dirt and moisture, is carried in a cradle attached to the running gear of one truck, the generator being usually driven from one axle by a belt, both driving and driven pulleys being

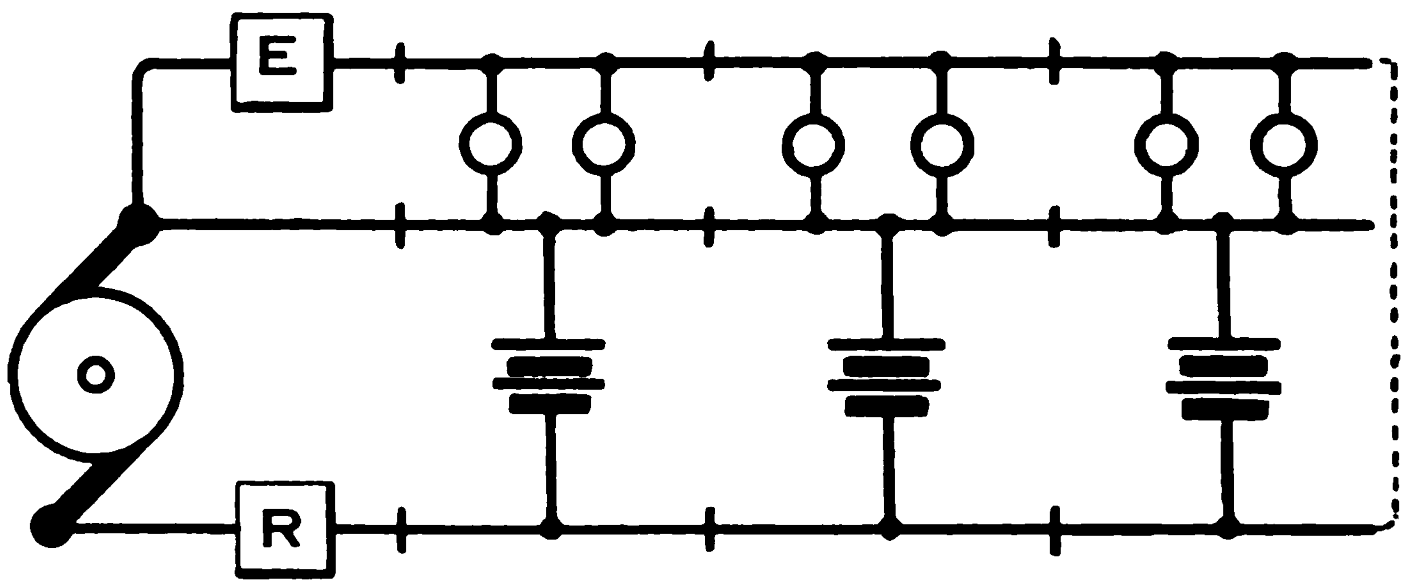


FIG. 1005.

provided with flanges to insure the belt staying on. The generator charges the storage battery, which is usually a 16-cell equipment rated at 30 volts. In this system it is more difficult to maintain a constant voltage than with either of the preceding systems, because of the fact that the speed of the generator varies through wide limits with the speed of the train; and the generator must furthermore be capable of operating equally well in either direction. An ordinary shunt generator does not possess characteristics suitable for this service. To insure a constant voltage under variable speed, more or less complicated regulating devices are required. Some generators built for the purpose of charging batteries on automobiles have inherent characteristics which adapt them for this work. But they are generally of small capacity. Furthermore, the axle-driven generator with its accompanying regulating devices was perfected before the

introduction of the small charging dynamo now so commonly used on automobiles.

To prevent the candle power of lamps from varying widely, automatic regulators must be provided which will hold the voltage constant at the lamp while the voltage of the battery varies between the extremes of full charge and complete discharge. In addition to this the regulators must prevent voltage variation due to change in speed of the generator itself.

One mechanical method of regulating the generator voltage involves the use of a slipping clutch. The speed of the generator may thus be held constant while the speed of the train varies.

The more general method involves regulation by electrical means, first of the lamp voltage by automatically inserting resistance in the lamp circuit, or in the field circuit of the generator; and second, by employing the armature reaction of the generator itself to hold the voltage of the machine constant.

The principle of voltage regulation employed in the Gould system is illustrated in Fig. 1004. This regulator employs a pile of carbon discs, *C*, connected in series between the battery and the lamp circuit. If the voltage of the battery, *B*, rises above that for which the lamps are designed, as would be the case toward the end of a charge, the pressure on the lamps, *L*, will rise. This will cause the circuit through the solenoid *S*, in shunt with the lamps, to increase. As the solenoid raises its plunger, it operates through a connecting lever to increase the pressure upon another stack of carbon discs, *R*, thereby lowering their resistance and permitting an increase of current through the solenoid *T*. The upward motion of the core of this solenoid releases the pressure on the carbon stack *C*, the resistance of which will thereby be increased. This causes the excess of pressure above that required by the lamps to be absorbed by *C*. As the operation of solenoids *S* and *T* depends upon an actual alteration of the lighting voltage, the pressure on the lamps cannot be held absolutely constant, but the variation is slight. The reason that the two solenoids are employed is to increase the sensitiveness of the system. Solenoid *S* acts as a relay and transfers through *R*, to the solenoid *T*, the impulse which it receives, thereby producing a magnified effect upon *S*. That is to say, a very slight alteration in line voltage affects *S* comparatively slightly. But because of the sensitiveness of the carbon stack *R* to changes

in pressure, a slight alteration of S varies, to a magnified degree, the current through the solenoid T. It is therefore able to produce a large alteration in the pressure upon C and thereby check any great rise in voltage.

The generator voltage employed to charge the battery or light the lamps directly is regulated by altering the pressure upon a stack of carbon discs in series with the shunt field of the generator. The carbon pile is acted upon by two solenoids, V and F. The solenoid V is connected in shunt with the line and therefore depends upon changes in generator voltage and responds to the slightest alteration of speed. The solenoid F is connected in series with the storage battery across the line and is influenced solely by variation of battery current.

A pole-changing switch, *P.C.*, operates automatically to connect the generator to the battery in the proper way, regardless of the direction of rotation of the generator. In some systems the rocker arm is mounted so lightly that the friction of the brushes on the commutator will rotate brushes and arm 180 electrical degrees in either direction and thus insure the proper polarity for the delivered current no matter which way the generator revolves.

Assuming the pole-changing switch to have closed, as the generator rises in speed the shunt winding of the automatic main switch K is energized. At a speed of about 12 miles per hour, this solenoid raises its core and closes the switch K. Current immediately commences to pass from the generator G through the solenoid F, battery B, and back through the series winding of K to the negative side of the generator. This current is in such a direction as to supplement the pull of the shunt winding and thus hold the switch K firmly closed. But should the generator slow down to such an extent as to allow the battery to discharge through the generator, the reversal of current in the series winding of the switch K operates differentially with respect to the shunt winding and allows the switch to drop open. This prevents motoring of the generator. As the speed of the generator accelerates, its voltage rises and the charging current into the storage battery also increases. This increase of current causes the solenoid F to raise its core, thereby relieving the pressure previously exerted by the weight of the core on one end of the carbon stack D. This causes the resistance in the field of the

generator to be increased and the voltage to be lowered. As the line voltage rises, due to increased generator speed, the solenoid *V* is strengthened and raises its core, thereby reducing the pressure on the right-hand end of the carbon stack *D*, still further increasing the resistance in the generator field circuit and lowering the voltage.

There are numerous other systems in which the methods of regulating the lamp voltage as well as the charging current vary widely.

For long runs with solid trains, the head-end system, with one generator taking care of the storage battery charging and lighting for the entire train, is the most economical.

If the runs are short and the cars lie over for considerable time in terminal yards, the straight storage system is the most economical, provided the same equipment is always used for the same runs.

Where entire independence of operation is desired and where equipment is transferred from one system to another, and where the cars are apt to be gone for a considerable length of time, the axle-generator system is the most flexible and has proved the most satisfactory.

SECTION XVIII CHAPTER V

AUTOMOBILE ENGINE IGNITION, STARTING AND LIGHTING

TRAIN LIGHTING

1. Explain the general plan, advantages and disadvantages of the "straight storage" system of lighting for railroad trains.
2. Explain the general plan, advantages and disadvantages of the "head-end" system of lighting for railroad trains.
3. Explain the general plan, advantages and disadvantages of the "axle-generator" system of lighting for railroad trains.
4. Explain the general plan of regulator employed for governing the charging of storage battery and the regulator for governing the voltage of the lamp circuit used with the axle generator system of the Gould Company. Sketch.

TRANSMISSION OF POWER

THE FLOATING-COIL CONSTANT-CURRENT TRANSFORMER

Series arc light generators were not practical in sizes much larger than 150 lights capacity. They therefore absorbed a comparatively small amount of power and were not as efficient as machines of several thousand kilowatts. The development of a special type of transformer permitted the abandonment of the series arc light generator as it was found that a constant current could be obtained from a constant potential alternator by means

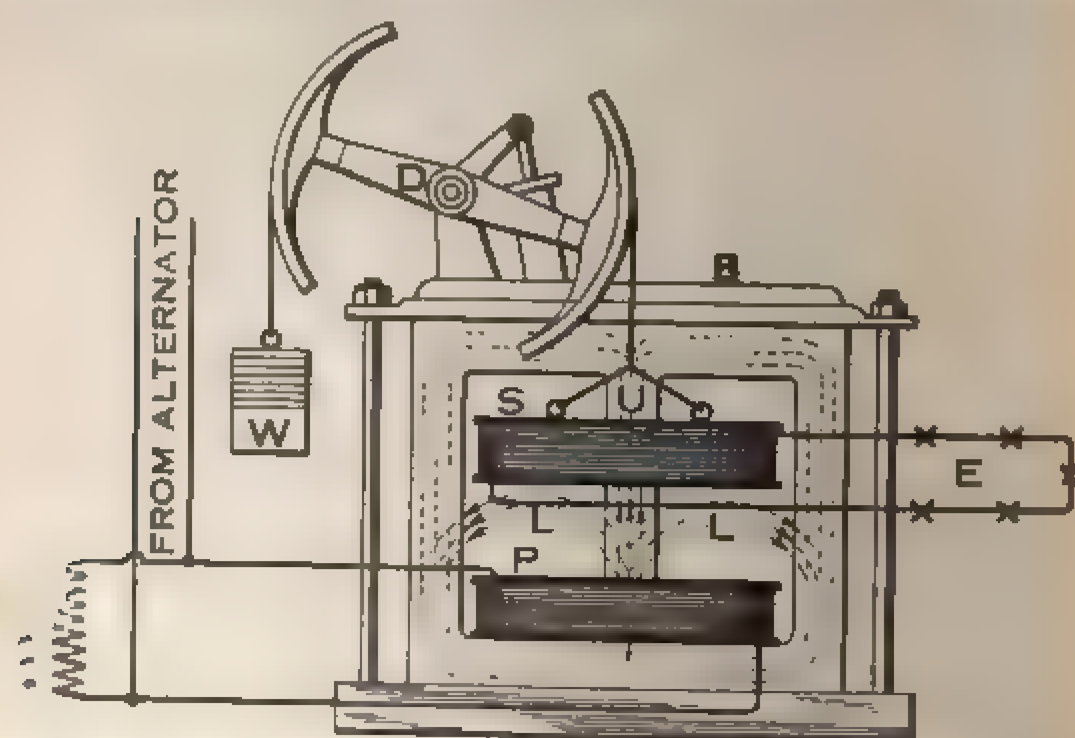


FIG. 1006.—Principle of constant-current floating-coil transformer.

of this special transformer. All alternators today are constant potential machines. By means of the usual constant potential transformer, *A*, Fig 1006, the pressure is reduced to 220 volts or 110 volts for lighting incandescent lamps, *C*, in multiple. By means of the so-called **floating-coil** transformer, *B*, Fig 1006, a constant current for a series circuit may be obtained in which the current will not vary more than one-tenth of an ampere throughout the greatest possible variation in load The primary coil, *P*, supplied from a constant potential alternator, surrounds

a central core of iron which divides in two parts in multiple, forming a structure similar to that used in the shell type of transformer. This primary is fixed in the bottom of the core. Surrounding the core above the primary is the secondary coil, *S*. This coil floats in space, being attached to the lever, *D*, on one end and partially supported by the counter weight, *W*, on the other end Through flexible connections a series of street lamps, *E*, is supplied. When current is impressed upon the primary, a secondary voltage will be induced which supplies the load. The secondary current is practically in opposite phase to that in the primary, so that the magneto-motive-force of these two coils will be in opposition to each other. The reaction of the secondary current will cause some of the magnetic flux which passed through it and the central leg of the transformer to be diverted out from under it, returning through the outside legs to the bottom of the core. The reaction of this current causes the coils to repel each other. The secondary coil therefore floats, as it were, on this leakage flux. The repulsion between the two coils, plus the counter weight, *W*, balances the force of gravity on the secondary coil.

To turn out lamps on the secondary circuit they must be short-circuited. This would reduce the resistance of that circuit. The immediate effect would be to cause the current to rise. This would produce a greater repulsion between the primary and secondary. The secondary would therefore move up until additional leakage flux, *L*, was diverted beneath it to such an extent as to lower the voltage induced therein until the current was reduced to practically the same value as before, after which the coil would again float stationary in space. If, on the other hand, additional lamps were cut in series on the secondary circuit, the current would fall The repulsion between the two coils would then go down and the secondary coil would move toward the primary, thus permitting more of the leakage flux to pass through it. When this increased flux raised the voltage sufficiently to restore the current to the original value, its downward movement could cease. The secondary coil therefore always floats at a point where the secondary current will be maintained at a fixed value, the particular value in any case being determined by the amount of counter weight, *W*. The lighter the counter weight the greater the current The heavier

the counter weight the smaller the current. A small floating coil transformer, with a single primary and a single secondary, each built in two sections, which are rigidly attached to each other, manufactured by the General Electric Company, is shown in

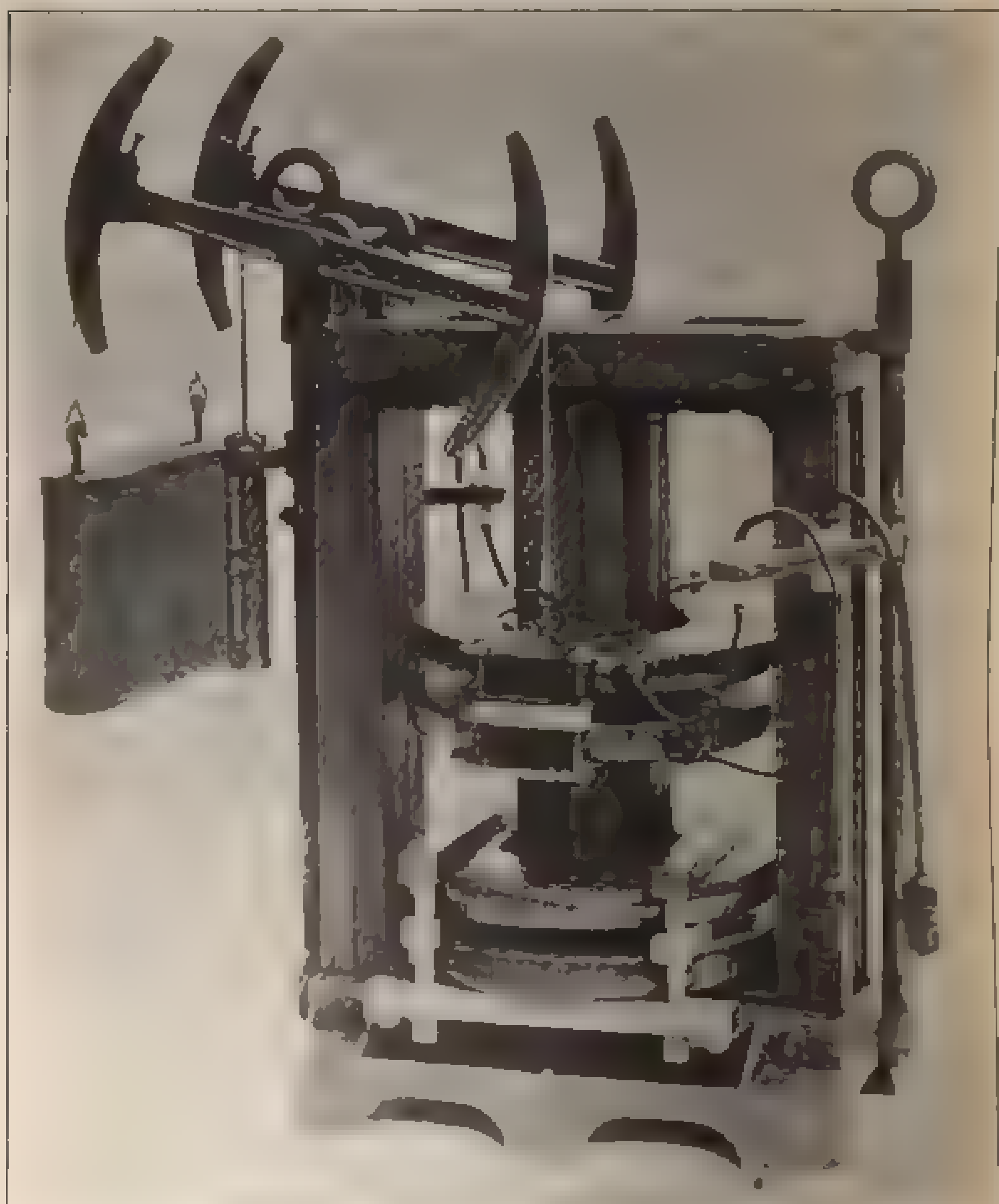


Fig. 1007. General Electric constant-current floating-coil transformer

Fig 1007 This permits two circuits to be taken from the single secondary, thus avoiding the high potential which would be involved in a single circuit Large transformers of this type have two moving coils and two stationary primary coils which are not rigidly attached to each other. In that case the two primaries

are at the extreme top and bottom of the central member and the secondaries move from positions immediately adjacent thereto away from the primaries and toward each other at the center. The two secondaries are counter-balanced against each other. The counter weight then opposes their movement from the primary instead of aiding it as when there is but one secondary.

As these transformers depend for their regulation upon the leakage flux, the power factor involved is very poor. It is 75%

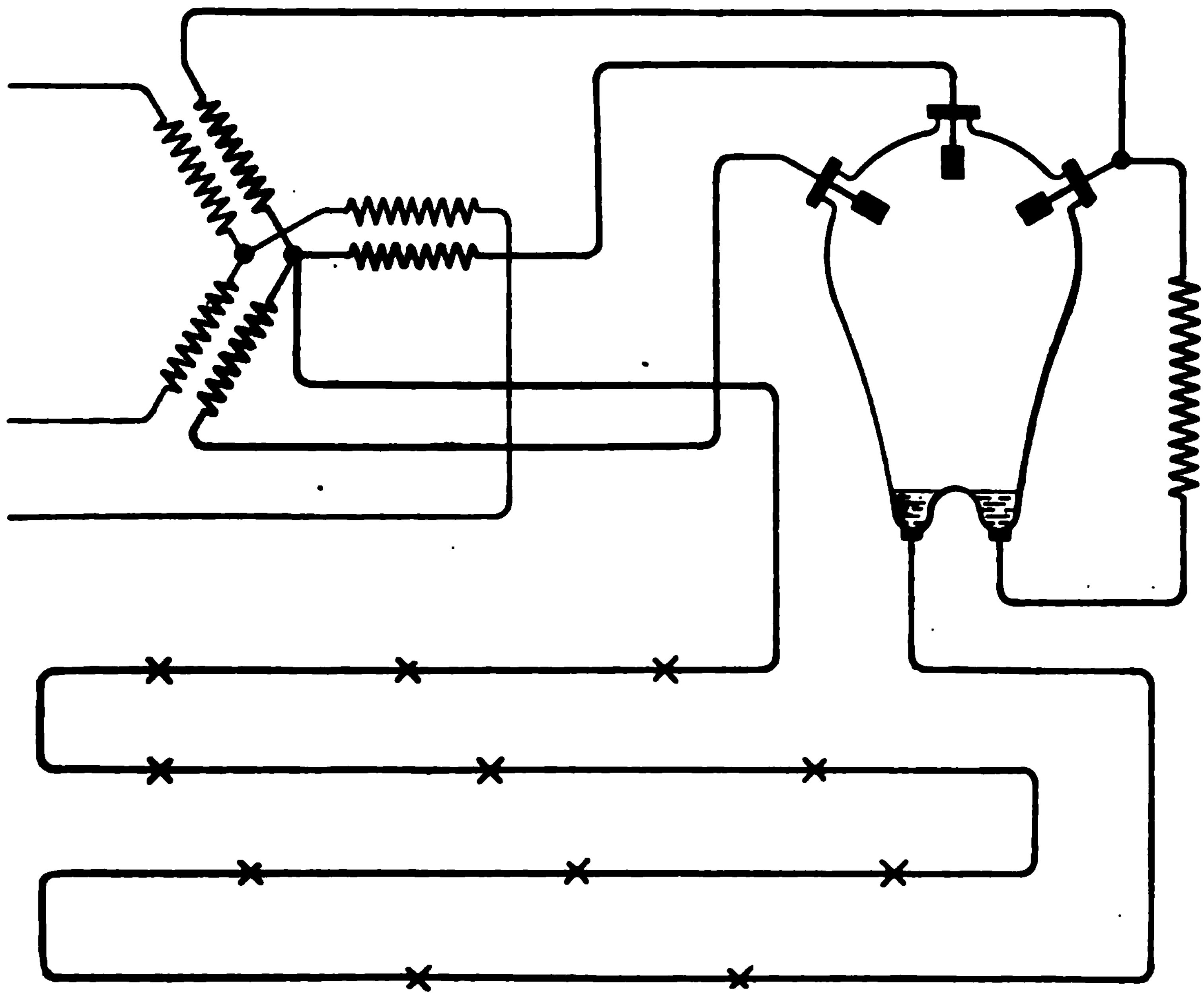


FIG. 1008.—Circuits of three-phase constant-current transformer and mercury rectifier for series direct-current arc-light circuit.

to 85% at full load and goes down directly with the load. The range of load is approximately from 25% to 100%, for the voltage induced in the secondary winding will be at least 25% of the maximum voltage when the primary and secondary are as far apart as possible. The efficiency is between 95 and 96%.

To put the transformer in action the secondary circuit is closed on the lamps, the counter weight *W* is pulled down and the windings separated as far as possible. The primary is then put into circuit with the source and the counter weight released.

The secondary coil then floats down into position until the current has risen to the particular value for which the counter weight W is adjusted. Thereafter the variation in current under the widest variation in load will not be more than one-tenth of an ampere.

These transformers are used for supplying current both for incandescent and arc-light series circuits. For incandescent lighting the alternating current is just as satisfactory as direct. For arc lighting the mercury rectifier is employed in connection with these transformers because of the higher efficiency of the direct-current, as compared with the alternating-current arc. Fig. 1008 shows the application of the mercury rectifier to a three-phase circuit and the direct-current lighting circuit attached thereto. Here the direct-current leading from the mercury rectifier terminals is passed into the arc-light circuit and then returned to the neutral point of the Y-connected secondaries of the transformers. For three-phase circuits, three single-phase regulators may be used, one across each phase. Or they can be furnished in pairs with an auxiliary auto transformer to give a balanced load. Where three regulators are used the auto transformer may be omitted.

Where incandescent lamps are employed in series, some provision must be made for maintaining the continuity of the circuit when a filament burns out. This is usually accomplished by bridging the lamp terminals with two small aluminum discs separated by a thin piece of chiffon veiling or similar material. Series incandescent lamps usually require between 10 and 20 volts each. This pressure is so low that the light insulating film is not broken down. If, however, the lamp filament fails, the potential across its terminals rises. This is sufficient to puncture and entirely destroy the film, allowing the two aluminum discs, which are maintained under spring pressure, to come into contact with each other and short-circuit the lamp terminals, thus preventing the circuit from being interrupted. Where arc lamps are connected in series an individual magnetic cutout is placed in each arc lamp to short-circuit the lamp should the electrodes become separated.

SECTION XIX CHAPTER I

TRANSMISSION OF POWER

THE FLOATING-COIL CONSTANT-CURRENT TRANSFORMER

1. Sketch and explain the construction and principle of operation of the "floating coil," constant-current transformer.
2. For what purpose is this type of transformer used? Why?
3. What is the efficiency, power factor and degree of regulation obtained with this type of transformer?
4. Sketch a three-phase mercury rectifier and floating coil transformer used for deriving a single series arc light circuit from a three-phase source.

SECTION XIX CHAPTER II

TRANSMISSION OF POWER

THE THREE-WIRE SYSTEM

The Edison three-wire system was devised for the purpose of transmitting power at 220 volts and utilizing it at 110 volts, thus reducing the transmission line loss. It has already been set forth that the copper required for transmitting a given amount of power a given distance with a fixed loss is inversely proportional to the square of the voltage of transmission. Thus to transmit a given amount of power at 200 volts will require one-fourth the total copper required to transmit the same power the same distance with the same loss at 100 volts. To prove that this is so, consider the calculation shown in Fig. 1009. Here 10,000 watts

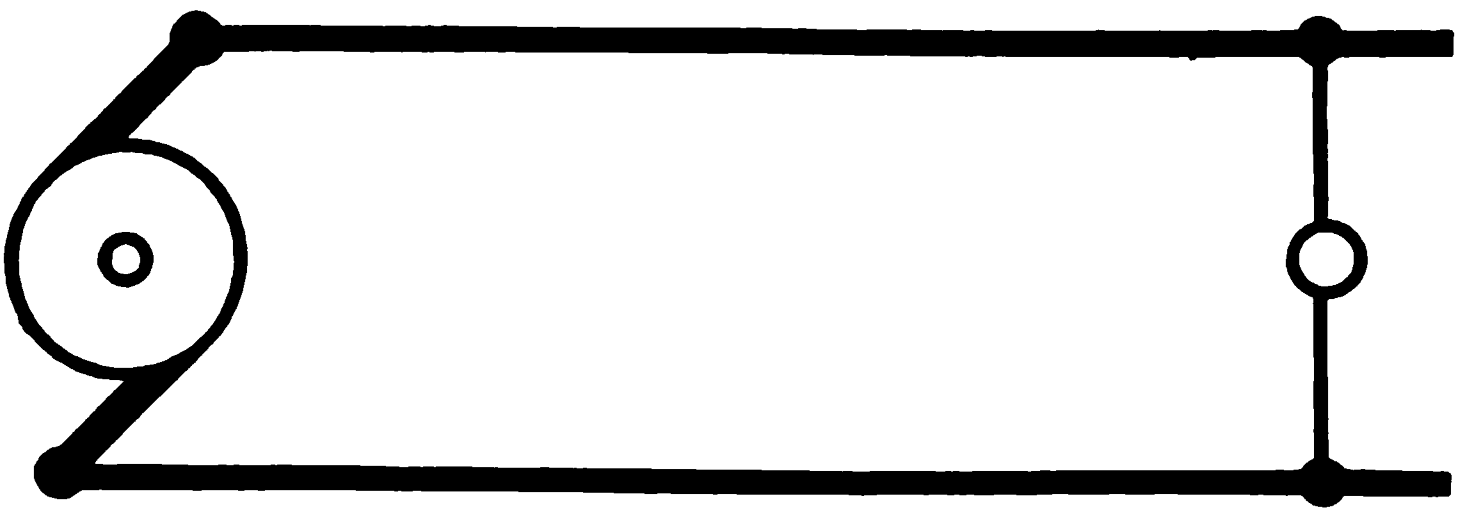


Fig. 1009.—100 amperes × 100 volts = 10,000 watts; resistance of line = 0.1 ohm, loss = 10% = 10 volts. 10 volts ×100 amperes = 1,000 watts lost.

are delivered by a generator for transmission in the form of 100 volts and 100 amperes through a circuit the resistance of which, exclusive of the load, is 0.1 ohm. The current of 100 amperes flowing through this resistance will involve a loss of 10 volts, which is 10% of the generated voltage. A loss of 10 volts and 100 amperes equals 1,000 watts. Deducting this from the 10,000 watts produced leaves 9,000 watts delivered at the load.

Next consider Fig. 1010. Here a line is shown having a total resistance of 0.4 ohm resistance instead of 0.1. It is obviously of one-fourth the cross-section. To transmit 10,000 watts at 200 volts will require but 50 amperes. Fifty amperes passing through the line resistance of 0.4 ohm will cause a loss of 20 volts, which, as before, is 10% of the generated voltage. Twenty

volts times 50 amperes equal 1,000 watts. Deducting this from the 10,000 watts generated leaves 9,000 watts delivered. Thus in the two cases the same power is generated, the same power is lost and the same power delivered. The copper required in the

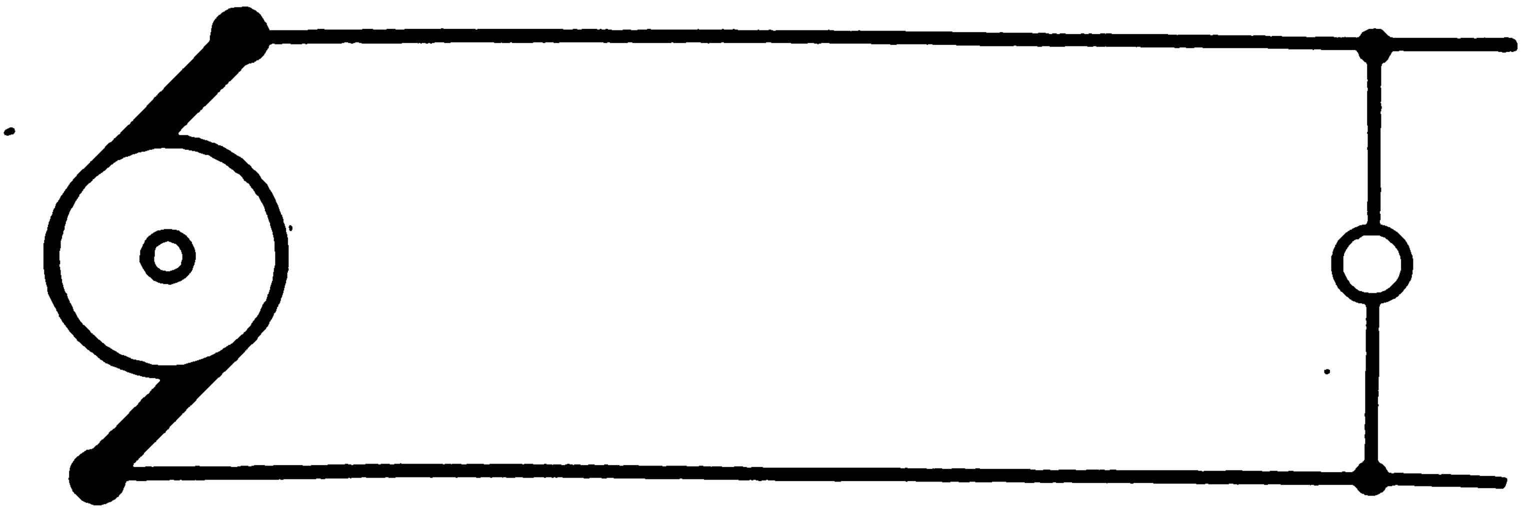


FIG. 1010.—50 amperes × 200 volts = 10,000 watts; resistance of line = 0.4 ohm, loss = 10% = 20 volts. 20 volts × 50 amperes = 1,000 watts lost

second case, however, is one-fourth that required in the former. This is because the current transmitted is halved and the actual voltage lost is doubled.

In the Edison system, two generators, *A* and *B*, Fig. 1011, each supplying 100 volts, are connected in series. Two lamps, *C* and

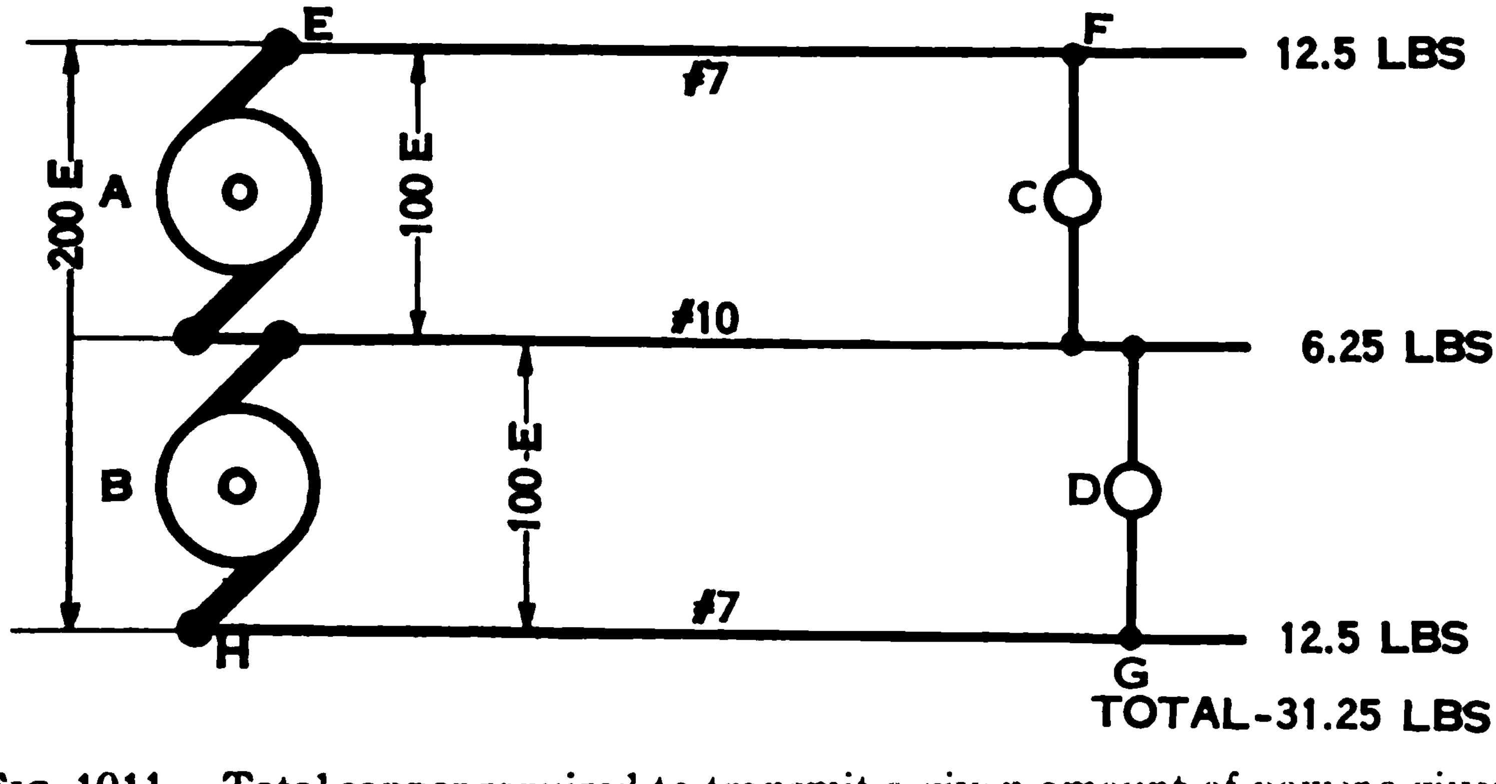


FIG. 1011.—Total copper required to transmit a given amount of power a given distance on the three-wire system with a fixed loss.

D, are likewise connected in series. The current flowing through this circuit will pass out from the point *E* to the point *F*, thence through the two lamps in series and back from *G* to *H*. The same current that flows through *C* passes through *D*. In Fig. 1012, twice the current would be required to light two lamps, for

they are connected in multiple. As the same power is transmitted in both cases it is evident from the foregoing discussion that, if the upper wire in Fig. 1012 weighed 50 pounds and the lower wire weighed 50 pounds, the total weight for both lines would be 100 pounds. In Fig. 1011, the transmitting voltage beign double, the size of each of the two outside wires could be made

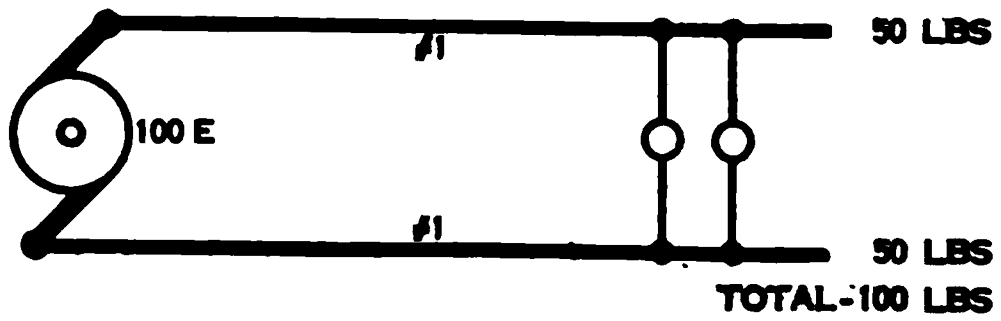


FIG. 1012.—Total amount of copper required to transmit the same amount of power transmitted in Fig. 991, the same distance, on a two-wire system with the same total loss and the same voltage at the lamps.

one-fourth of that in Fig. 1012, or 12½ pounds. If, however, there was no middle wire and one of the lamps was turned off, it would interrupt the circuit for the other, and as it is undesirable to put two lamps out at once, a neutral wire is employed, returning to the middle point between the two generators. The amount of current carried by this wire varies with the number of lamps on

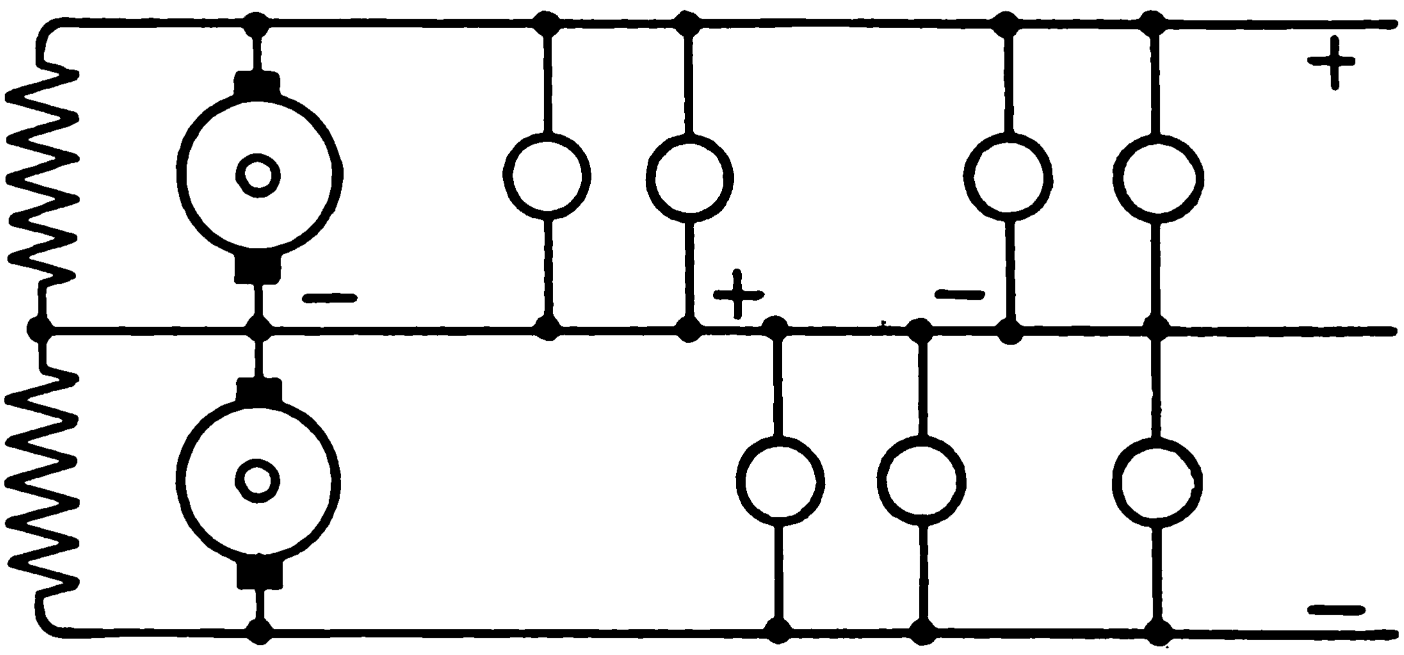


FIG. 1013.—Various currents in neutral wire on the three-wire system.

one side of the system in excess of those on the other side at any particular instant. It therefore cannot be regulated or calculated. In some installations the current required is such as to necessitate a neutral twice the size of an outside wire. In buildings, the neutral is generally of the same size; in feeders, one-half the size. Assuming it in this case to be one-half the size of

an outside wire, it would weigh $6\frac{1}{4}$ pounds. The total weight for the three wires would therefore be $31\frac{1}{4}$ pounds. Thus it has been customary to say that the three-wire system requires $31\frac{1}{4}\%$ of the copper required on the two-wire system. Fig. 1013 shows the original arrangement of the Edison three-wire system. Two 110-volt generators were placed in series and the load divided as evenly as possible between the two sides of the system. The economy of this system was only fully realized when the load was exactly balanced. To whatever extent one side demanded more current than the other, to that extent that side of the system operated with the economy of the two-wire system only, instead of that of the three-wire system. Lamps *A* and *B* being in series, the neutral carries no current as far as they are concerned. Lamps *C* and *D* may be removed from each other some distance so that the current flows through *C* and thence through

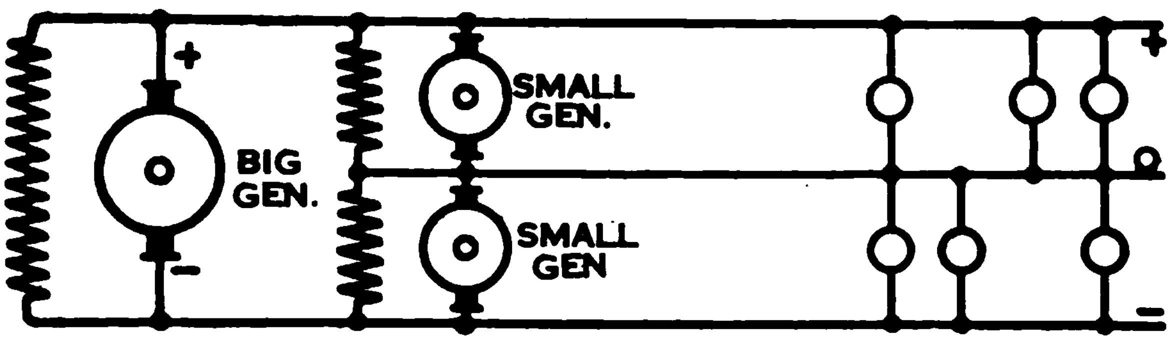


FIG. 1014.—One large 220-volt generator to care for the balanced load and two small 110-volt generators to care for an unbalanced load on the three-wire system.

the neutral until it finds a circuit through the lamp *D* to the negative side of the line. The current through *E* flows away from the station through the neutral until it finds a path through *F* to the negative wire, while the current through *G* must return through the neutral wire to the station. Thus the neutral may be positive and negative and neutral all at the same time in various portions of its length.

Lamps are commonly built for 110 volts and connected on one side of the system. Small motors are connected in the same way. In certain localities motors over one-half horse power are required to be wound for 220 volts and are connected across the two outside wires of the system. This prevents unbalancing of the system by motor loads.

As the size of the load on the three-wire system grew in large cities it became desirable to use one large 220-volt generator connected to the positive and negative wires to carry the bulk

of the balanced load as in Fig. 1014, and two small engine-driven generators of 110 volts each, connected in series, across the lines with a tap from between them to supply the neutral and care for the unbalanced load. The maximum unbalanced load that could be handled was limited to the capacity of one of the small generators. Should the unbalanced load exceed this capacity, the load on the small set could be reduced by throwing an artificial load on the other side of the system. To whatever extent the load was thus balanced, to that extent the two small machines would be relieved and the additional load would be carried by the large generator. Should a large unbalanced load be thrown suddenly on one side of the system in excess of the capacity of the one small generator, its circuit breaker and fuses

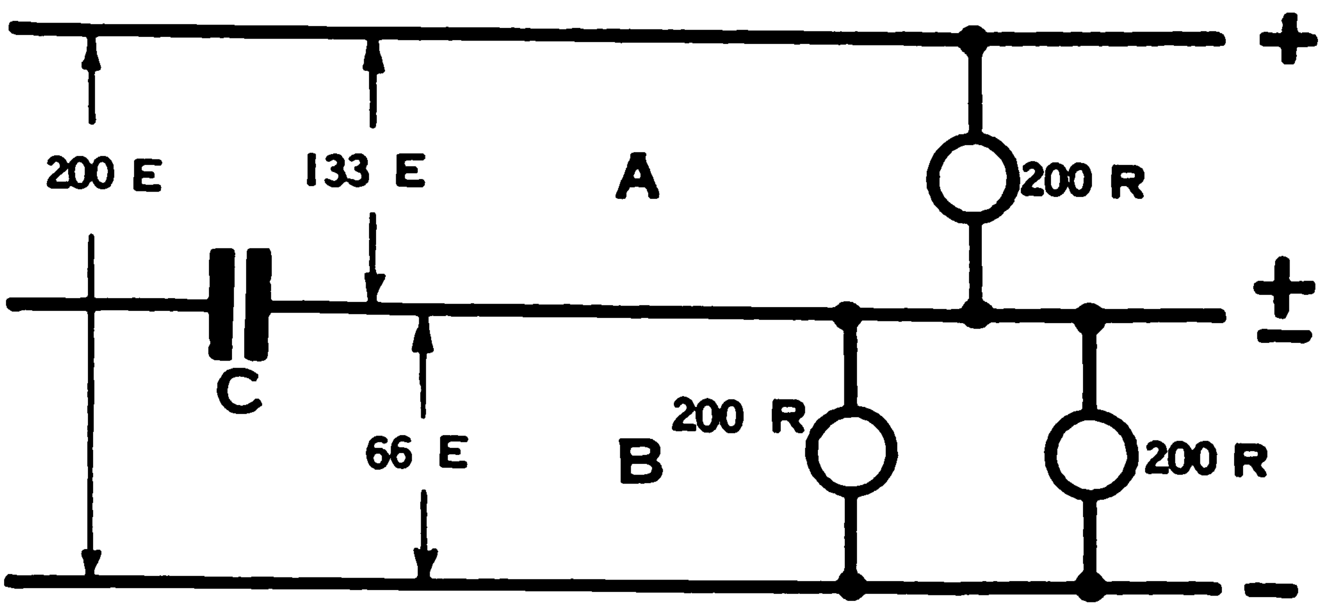


FIG. 1015.—Effect of opening the neutral on an unbalanced three-wire system.

might open the circuit, thus breaking the neutral wire. The effect of opening the neutral on a three-wire system when the load is unbalanced is to produce a great difference in voltage on the two sides of the system. To illustrate this, consider Fig. 1015. Here one lamp of 200 ohms is connected on the *A* side of the system, and two lamps of 200 ohms each are connected in multiple on the *B* side, with 200 volts across the two outside wires. The object is to maintain this voltage evenly divided between the two outside wires or 100 volts on each. Should the neutral be opened at *C* from any cause, the result will be as follows: A 100-volt 200-ohm lamp requires $\frac{100}{200} = \frac{1}{2}$ ampere. The two lamps on the *B* side combined have 100 ohms resistance. This in series with the one lamp on the *A* side makes a total of 300

ohms. With the neutral open, 200 volts will establish in this circuit $\frac{E}{R} = I$. $\frac{200}{300} = \frac{2}{3}$ ampere, in the lamp on the *A* side. $I \times R = E$. $\frac{2}{3} \times 200 = 133\frac{1}{3}$ volts on *A*. $\frac{2}{3} \times 100 = 66\frac{2}{3}$ volts on *B*. Thus, instead of an equality of voltages, the voltage goes up on the *A* side and down on the *B* side in proportion to the combined resistances. The ratio of voltage is as 2 to 1, which is the same as the ratio of the resistances on the two sides. The upper lamp gets ⅔ of an ampere instead of ½, and each lower lamp gets ⅓ of an ampere instead of ½. The upper lamps are thus overloaded and the lower lamps operated at reduced current. The greater the unbalancing of the load the greater the unbalancing of the voltages. Thus it is entirely possible for the voltage on one side to rise to such an extent as to burn out a large number

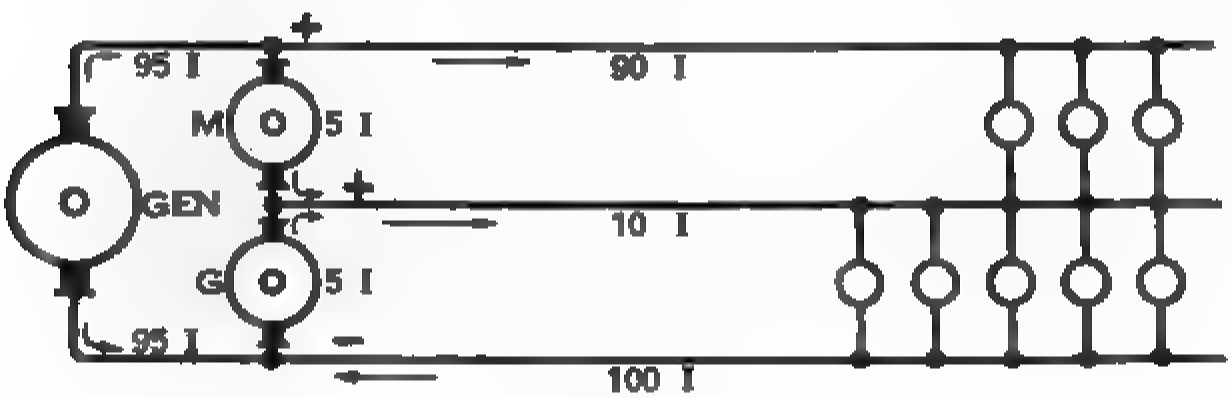


FIG. 1016.—Motor-balancer set for caring for unbalanced load on three-wire system.

of lamps should the neutral be opened. Every precaution is therefore taken to insure that the neutral circuit shall be maintained closed.

Another method of supplying the unbalanced load is by employing one or more large generators of 220 volts each shown in Fig. 1016, with a motor-balancer set *M-G*, whose armatures are connected in series across the lines with a tap to the neutral wire, the shafts of the two machines being rigidly coupled. When the load is balanced these two machines float idly on the system with their fields across the line, absorbing only their stray power and field losses. If an unbalanced load is thrown on the negative side of the system, there is a demand for current between the neutral and negative wires. The difference of potential across these two wires causes a current to flow from between the two machines into this wire. This current coming from the lower

machine causes it to act as a generator, its counter e.m.f. now exceeding the drop across it. This current causes the machine to react through its shaft connection upon the upper machine, which acts as a motor to drive it. This causes a demand for current from the main generator. Now if the unbalanced load calls for 10 amperes, 5 amperes will come from the main generator down through the motor *M* to the neutral wire. Five amperes will also come up from the other machine *G* and unite with the former, making 10 amperes in the neutral, which supplies the unbalanced load. There are three circuits here involved, each supplying a different current and voltage. First, assuming a balanced load of 90 amperes, this current comes from the main generator at 220 volts over the positive wire, supplies the load and returns over the negative wire to the gen-

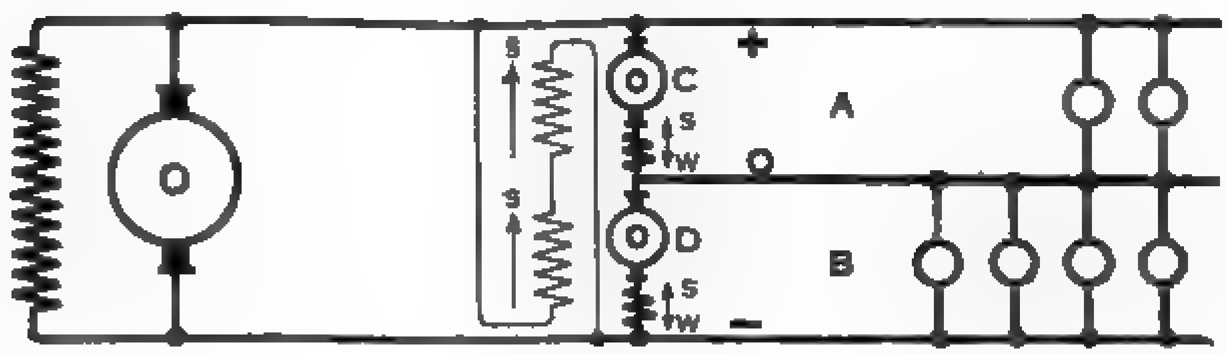


Fig. 1017.—Compound motor-balancer set for equalizing voltages on an unbalanced three-wire system.

erator. Second, to supply the unbalanced load, 5 amperes passes from the generator at 220 volts into the positive wire and down through the motor *M*. It there falls 110 volts in potential and then passes out over the neutral and supplies a part of the unbalanced load, falling the other 110 volts through it, and returning over the negative wire to the generator. Third, the 5 amperes and 110 volts lost in the motor are transformed into 5 amperes and 110 volts in the generator *G*. This machine then furnishes 5 amperes and 110 volts over the neutral wire, through the unbalanced load and back over the negative to the small machine *G*, where it originated. Neglecting losses, the voltage of each of the two sides of the system will be maintained at 110 volts. As a matter of fact, the motor must take in enough power to supply the losses in both machines of the set. Hence there will be a discrepancy of voltage, the positive or lightly loaded side tending to rise in voltage while the heavily loaded side tends to

fall. This may be partially corrected by using compound motor balancers as in Fig. 1017. In addition to the shunt winding, each machine has a series winding. The current may reverse in either of these windings, depending upon whether the excess of load is on the *A* side or the *B* side of the system. The machines in a motor-balancer set reverse their functions as motor and generator according to the location of the excess load. When the excess is on the *B* side, *C* is a motor and *D* is a generator. When the excess is on the *A* side, *D* is a motor and *C* is a generator. The double-headed arrows indicate that one direction of current, *S*, strengthens the field, while the other direction of current, *W*, weakens the field. Now should an excess load be thrown upon the *B* side of the system, current from the main generator flowing down through *C* passes through the series winding in such a direction as to weaken the field of this machine on its way to the

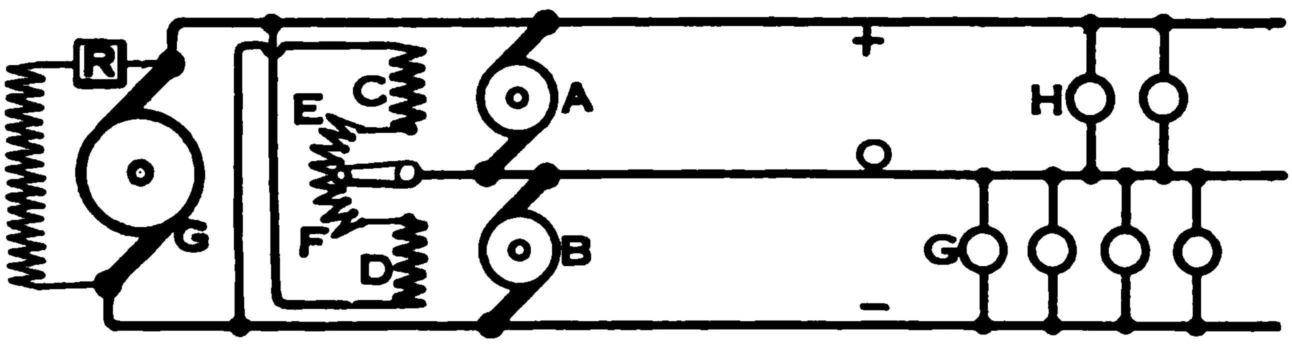


FIG. 1018.—Motor-balancer set with cross-connected fields for equalizing voltage on unbalanced three-wire system.

neutral. At the same time *D* is operating as a generator and sends current upward on its way to the neutral, passing through the series winding in such a way as to strengthen the field. This tends to raise the voltage on the *B* side and consequently lower it on the *A* side and thus maintain an equality of potentials.

A more widely used method of compensating for inequalities of potential is shown in Fig. 1018. Here the shunt fields are cross-connected so that the field *C* of machine *A* is connected across the armature of *B*, and the field *D* of machine *B* is connected across the armature of *A*. Now with an excess load at *G*, the tendency is for the potential to fall on the negative side of the system. As the field winding *C* is connected to this side, it is thereby weakened, and *A*, acting as a motor, speeds up, while the tendency for the voltage to rise on the positive side at *H* results in raising the excitation of the field *D* which supplies flux for the generator *B*. Thus the voltage of *B* is increased

and the fall on this side of the system prevented. The combined effect results in equalizing the voltage on the two sides of the system.

In all three-wire systems depending upon a balancer set for maintaining the potential of the neutral, a protection must be afforded against the possibility of a short circuit on one side of the system causing the full potential of the main bus to be im-

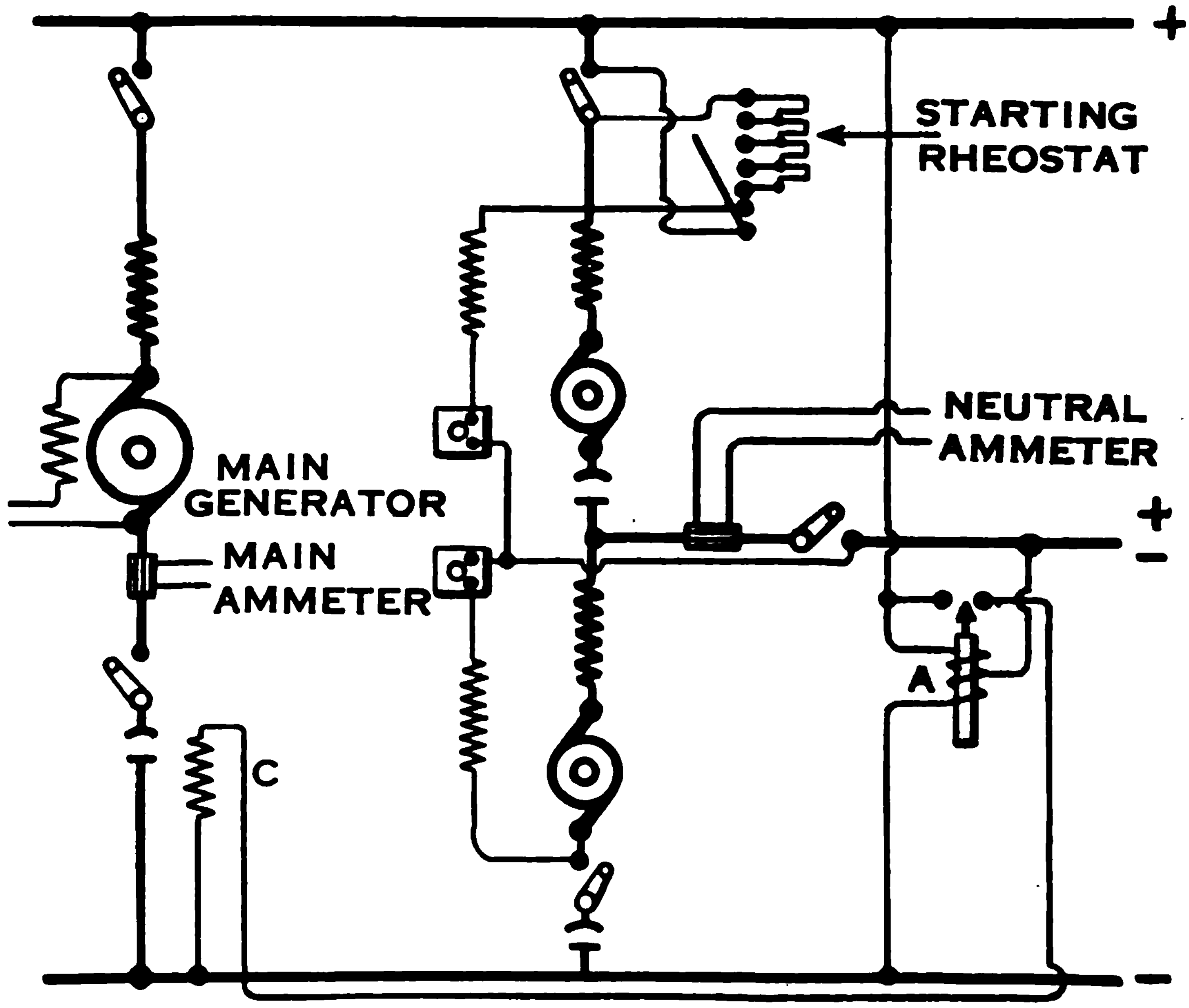


FIG. 1019.—Differential relay, *A*, for tripping circuit breaker on main generator in case of greatly unbalanced load on a three-wire system employing a motor-balancer set.

pressed upon the other side with destructive results to the lamps. This may result from the automatic disconnecting of the motor-balancer set due to short circuit, with automatic circuit opening devices, or, if the set is not balanced, from the flashing over of the commutator of the machine on the short-circuited side. One method of averting this and affording protection is to employ a differentially wound relay shown at *A* in Fig. 1019, with its coils connected across the two outside wires of the system and its contacts normally open. These contacts, when closed, provide

a circuit which energizes from the main bus, a tripping coil, *C*, on the circuit breaker of the main generator. The relay is inoperative as long as there is an equality of potentials on the two sides of the system. Abnormal rises of potential on either side, however, energize one winding of the relay more than the other, and the relay closes. Thus, although the actual load on the main generator has not reached a dangerous amount, the inequality of potentials which would endanger lamps operates to disconnect the source of supply from the system.

Fig. 1020 illustrates the three-wire generator employed for use on the three-wire system. The principle of this machine has already been explained. By means of two sets of balance coils which in effect are auto transformers connected to points in the winding on the armature corresponding to a two-phase

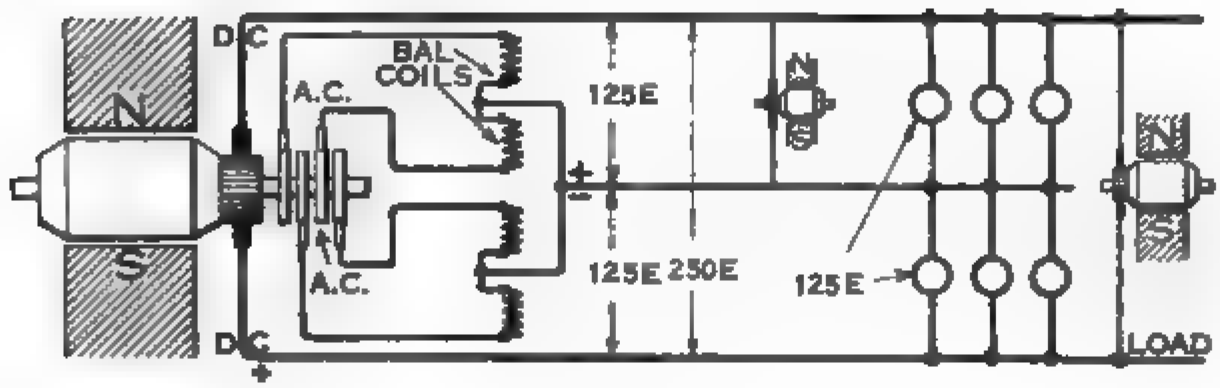


Fig. 1020.—Three-wire generator with external balance-coils for supplying three-wire system.

rotary, a neutral tap may be obtained which will insure the neutral wire being maintained at mid-potential between the two outside wires under widely varying loads. Fig. 1021 shows the general appearance of the three-wire generator built by the Westinghouse Electric and Manufacturing Company. The view is from the pulley end with bearing removed to show the connections of series, shunt and commutating pole windings. The compound winding on such machines is generally arranged so that the series coils on all the north poles are connected in the positive line, while the series coils on all the south poles are connected in the negative line.

Motor-balancer sets and three-wire generators cannot be operated on the same system at the same time, as the balance coils of the three-wire machine will act as a short circuit across the balancer set. If both types of machines must be operated

together, the neutral connection to the balance coils must be opened, and the three-wire machine is simply employed to carry the balanced load while the balancer set cares for any unbalanced conditions.

The majority of large direct-current power systems in the

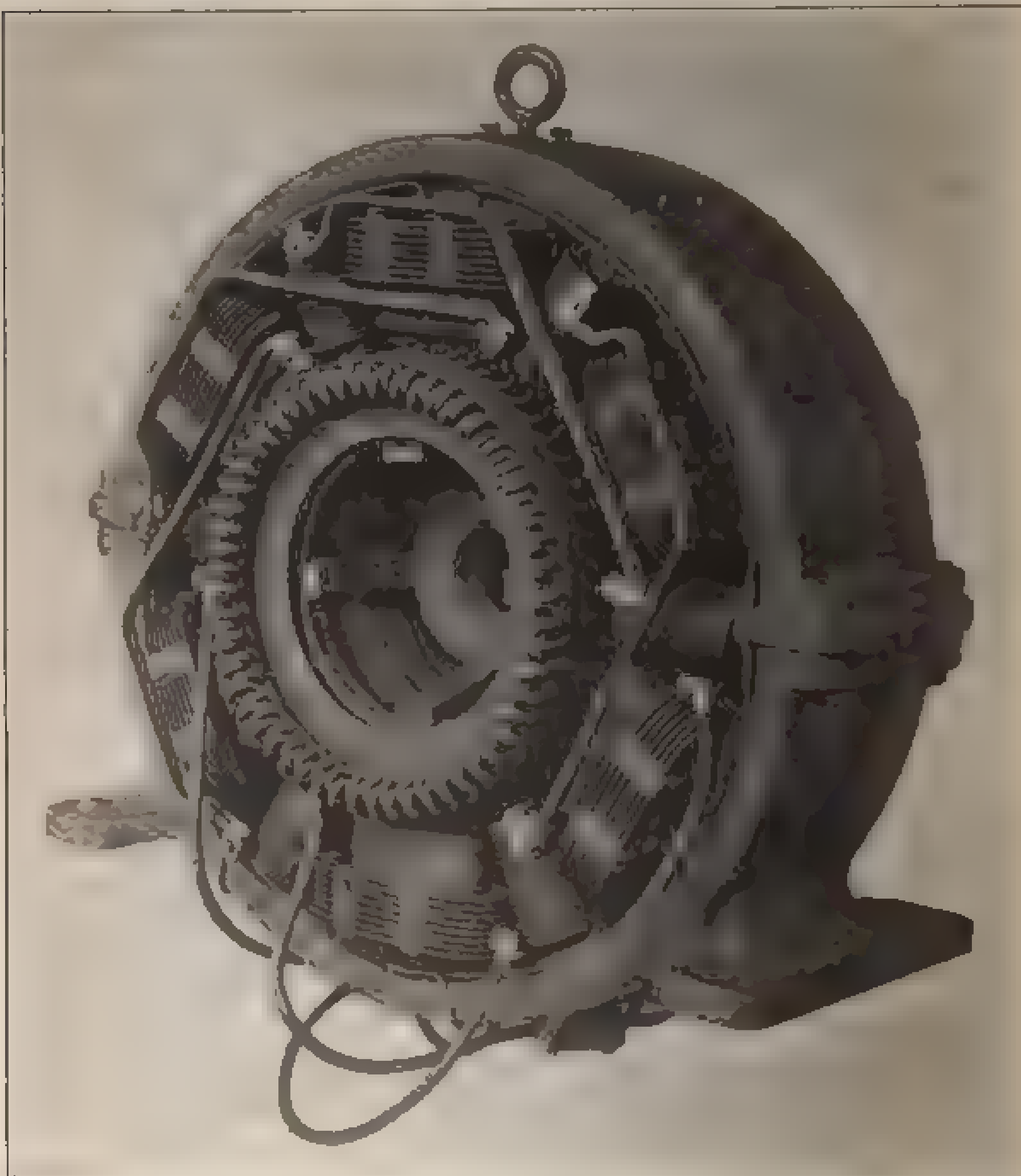


FIG. 1021.—Westinghouse three-wire generator showing connections of series, shunt and commutating pole windings and internal arrangement of parts.

principal cities today are not supplied from direct-current generators, as such machines cannot be made of more than a few thousand kilowatts capacity. In very large sizes they become expensive to build, and commutation is troublesome. Alter-

nators, however, may be made of almost indefinitely large capacity, 30,000 K.V.A. machines now being found in frequent use. Alternating current is transmitted at high potentials to substations, where it is transformed and passed through rotary converters. These rotary converters are located at convenient

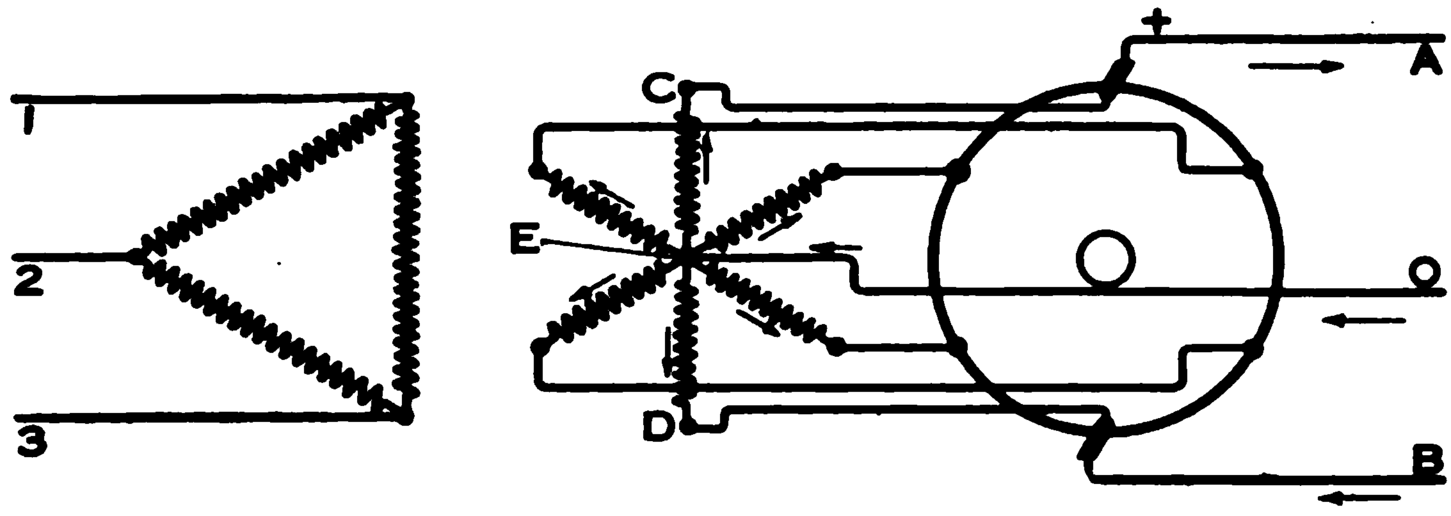


FIG. 1022.—Connections of secondaries of transformers for six-phase diametrical rotary converter.

points throughout the cities, and tie in on the direct current side to the low-voltage network, supplying current at 220 volts to the outside wires of the three-wire system. The neutral is maintained at a potential midway between the two outside wires, not by any connection to the rotary but by a con-

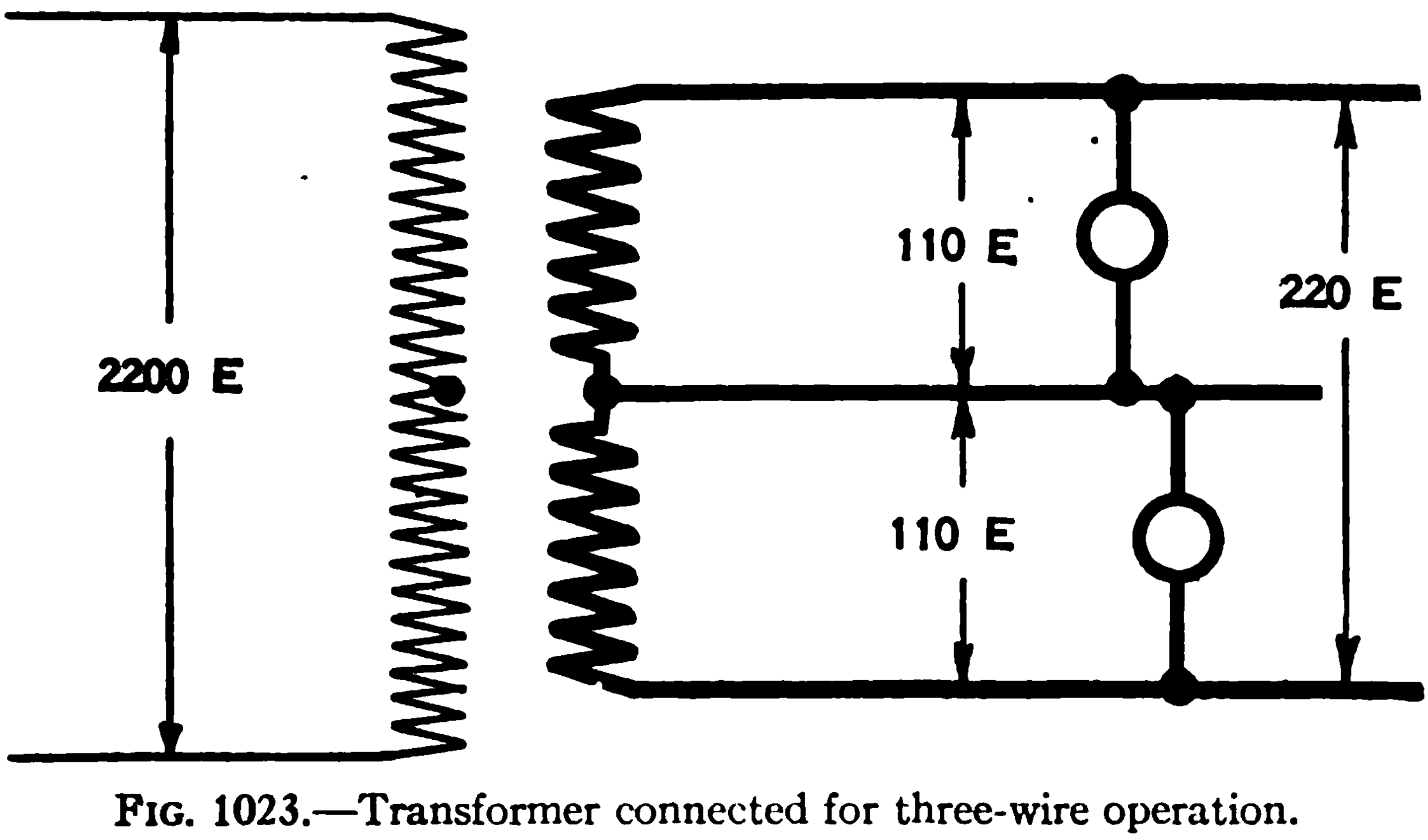


FIG. 1023.—Transformer connected for three-wire operation.

nection to the transformer which supplies the rotary. Fig. 1022 shows the general arrangement. Here a three-phase source, usually at 6,600 or 11,000 volts, supplies current over the wires 1, 2 and 3 to the high-tension side of the three single-phase or one composite transformer, which may be connected in

Δ The three low-tension windings are connected to the slip rings of the rotary which tap the armature winding at points 60 electrical degrees apart. From the D. C. brushes of the rotary, current is led over the wires *A-B* to the D. C load. Any unbalanced load takes current over the neutral, which current flows out from or returns into the middle point of the three low-tension windings of the transformers which are tied together at the point *E* as shown. This point is midway in potential between

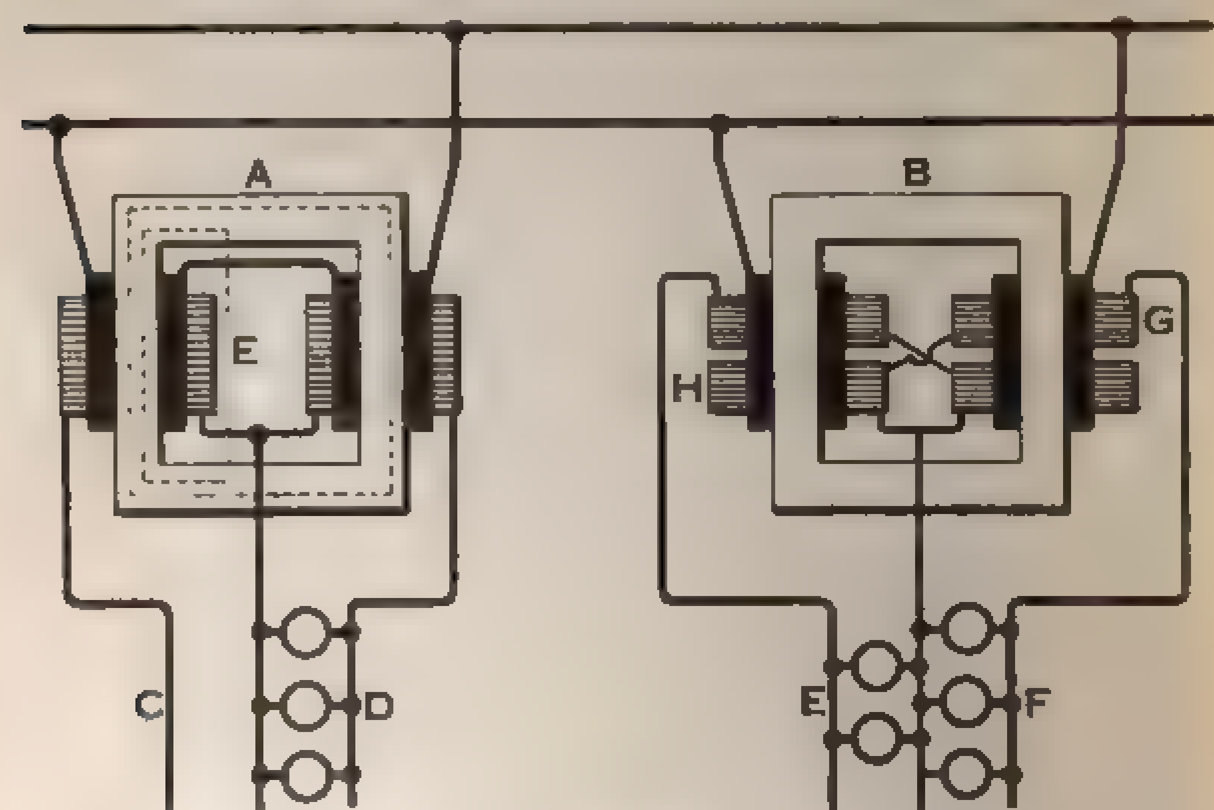


Fig. 1024

Ordinary core-type transformer not adapted for three-wire operation with unbalanced load.

Special arrangement of core-type transformer with distributed and interconnected secondaries specially adapted for three-wire operation.

the A. C. brushes *C* and *D*, and likewise midway between the D. C. brushes supplying the lines *A-B*.

In place of D. C. sources, transformers may also be used to supply the three-wire system as in Fig 1023. For this purpose a single transformer may be used with the high-tension sections in series on 2 200 volts and the low-tension sections likewise in series, furnishing 220 volts. An ordinary core-type transformer cannot be used for this purpose if one-half of the low-tension winding is on one leg and the other half on the other leg as shown at *A* in Fig 1024. In this case, should the load become greatly unbalanced as at *D*, the reaction of the magneto-motive-

force of that section of the winding supplying this load would divert some of the flux which passed through it into the leakage path, *E*, between the two windings. This would tend to lower the voltage on the side *D* and raise the voltage on the side *C*. If, however, the low-tension windings are divided as at *B*, one-half of the low tension, *G*, being placed on one leg, and the other half, *H*, on the other leg, the reaction of the current in these windings on the magnetic flux brought about by an overload at *F* would be equally distributed on both legs, and no leakage flux would occur between the windings. This tends to maintain an equality of potentials on both sides. The larger the transformer the more the low-tension winding should be sectionalized and distributed.

SECTION XIX CHAPTER II

TRANSMISSION OF POWER

THE THREE-WIRE SYSTEM

1. Explain the advantages of the 220-volt system over a 110-volt system with reference to the copper required.

2. Explain the advantages of a three-wire system over a two-wire system.

3. (*a*) Why must a neutral be employed on a three-wire system? What size should the neutral be made: (*b*) For ordinary housewiring? (*c*) For "feeders"?

4. What percentage of copper is required on a three-wire system compared with a two-wire system for delivering the same number of lamps the same distance with the same percentage of power lost in the line and the same voltage at the lamps?

5. How much current does the neutral wire carry? What determines it?

6. What was the original plan devised by Edison for supplying power on a three-wire system. Sketch.

7. What advantage has one 220-volt and two 110-volt generators over two 110-volt generators? Sketch.

8. What will be the effect upon the voltage impressed on the lamps, if the neutral wire is disconnected when the load is unbalanced? Explain fully.

9. If one side of a three-wire system has 100 40-watt, 110-volt lamps in circuit and the other side has 2 100-watt, 110-volt lamps in circuit, what voltage will be impressed on each group if the neutral fuse blows?

10. Explain the advantages and disadvantages of one large generator and a motor-balancer set to supply a three-wire system. Sketch.

11. What limits the amount of unbalanced load which may be cared for when motor-balancers are used?

12. A three-wire system is supplied by a 400-k.w., 220-volt generator and a motor-balancer set of 40-k.w. capacity on each end:

(*a*) What is the maximum number of 40-watt lamps which can be carried on both sides of the system with a balanced load?

(*b*) What is the total number of lamps which can be carried on each side of the system with the maximum permissible unbalanced load?

13. What is the advantage of the compound motor-balancer? Sketch.

14. What is the advantage of a motor-balancer set with cross-connected shunt fields? Sketch.

15. What is the object in providing for tripping the circuit-breaker on main generator in case of excessive overload on one side of a motor-balancer system? Why must this be done?

16. Explain the general construction of a three-wire generator for supplying a three-wire system.

17. Under what conditions may a three-wire generator be used for supplying a three-wire system?

18. Can 2 110-volt generators in series or a motor-balancer set be used in parallel with a three-wire generator? Why?

19. If a six-phase rotary converter is used to supply a three-wire system, to what point must the neutral of the system return? Sketch.

20. Can 2 110-volt transformers be used in series to supply a three-wire system? Sketch.

21. Can a single 220-volt transformer be used to supply a three-wire system? If so, under what conditions? Sketch.

SECTION XIX CHAPTER III

TRANSMISSION OF POWER

CALCULATION OF TRANSMISSION LINES

The line is a very important part of a power transmission system. One of the first questions that arises in designing a system for the transmission of power is the character and dimensions of the conducting circuit. In considering a transmission problem the layman's first question generally is: How much power will be lost in the line? To which the engineer replies: As much or as little as you please. If 100 kilowatts is to be transmitted 20 miles, it would be possible to design the line so that the entire energy would be wasted in heating the line, and none would be available at the receiving end. By using a larger conductor, only a portion of the 100 kilowatts would be lost, and some would be available at the load. If, in a given transmission line, 50 kilowatts represents the energy wasted in overcoming the resistance of the circuit with a certain size of wire, it is evident that, by installing another wire of the same size in parallel with the first, the loss would be reduced to 25 kilowatts, for, as the resistance has been halved, the loss would be halved. The question which the engineer must decide is: Would it pay to double the amount of copper in the line to save this 25 kilowatts? Now if the 25 kilowatts saved can be sold for a price which will yield something more than the interest on the cost of the additional copper required to save it, plus the extra cost of construction, then the investment might be wise. Seldom, however, can a transmission problem be reduced to such a basis. Usually there is some reserve in the capacity of the generating station so that the limit has not been so closely approached as to warrant the investment of any considerable additional amount of money in the transmission line. Furthermore, it is doubtful if a market for the power so saved could be found.

There are many factors which enter into the determination of a suitable percentage of loss to allow in a transmission line.

Three things must be considered:

First, the amount of power to be transmitted.

Second, the length of the transmission line.

Third, the voltage of transmission.

A considerable technical knowledge is necessary to intelligently decide what the per cent of loss should be in a given case. In general it may be said that the **per cent loss** may be **increased** with the **length** of the line and **decreased** with the **voltage** employed. For a given distance and voltage the per cent loss will, under certain conditions, be greater with large powers than with small powers.

The **diversity factor** of the load may also influence the permissible loss in the line. The diversity factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

Thus an industrial load of 1,000 K.W. and a lighting load of 1,000 K.W. might be supplied from the same station. As the industrial load would be required only in the daytime and the lighting load only at night, the copper for the transmission line from the generating station need only be sufficient to supply 1,000 K.W. instead of 2,000 K.W. The diversity factor in this case would be 50%. It refers to the maximum percentage of the connected load which may be demanded at any one time during the day. The problem of regulation is involved in the loss which is assigned. With no load the voltage at the receiving end will always be the same as that at the transmitting end. If the loss be fixed at 10%, it follows that, when full load is applied, the full loss of 10% will be encountered. This means that lamps and motors will suffer a drop in potential varying with different conditions of load from nothing up to the full 10%. Ten per cent change in lamp potential is very objectionable. Hence provision must be made for either automatic or hand-regulating devices for holding the potential uniform within reasonable limits at the load. Low-tension distributing networks will involve a loss of from 5 to 10% between the source of direct-current power and the distributing centers. In house wiring the loss in the mains entering the buildings may vary from 3 to 5%. The loss on the branch lines is usually 1%. These losses may total 10 or 15% from the source of direct current to the lamps.

When long-distance transmission lines are employed, the loss

will seldom be less than 5% and seldom greater than 15% on even the longest lines.

Circular Mil Formula for Copper Wire.—If a current of 10 amperes flows through a circuit shown in Fig. 1005, having an unknown resistance, and the potential drop across the terminals is found to be 50 volts, the resistance of this circuit may be expressed by the equation:

$$\frac{E}{I} = R. \qquad \frac{50}{10} = 5 \text{ ohms.}$$

Another expression for the resistance of the circuit can be obtained as follows:

$$R = \frac{10.6 \times l}{c.m.}.$$

Where:

10.6 = the specific resistance of one foot of copper wire having one circular mil cross-section.

l = the length in feet of the circuit.

$c.m.$ = the circular mils cross-section.

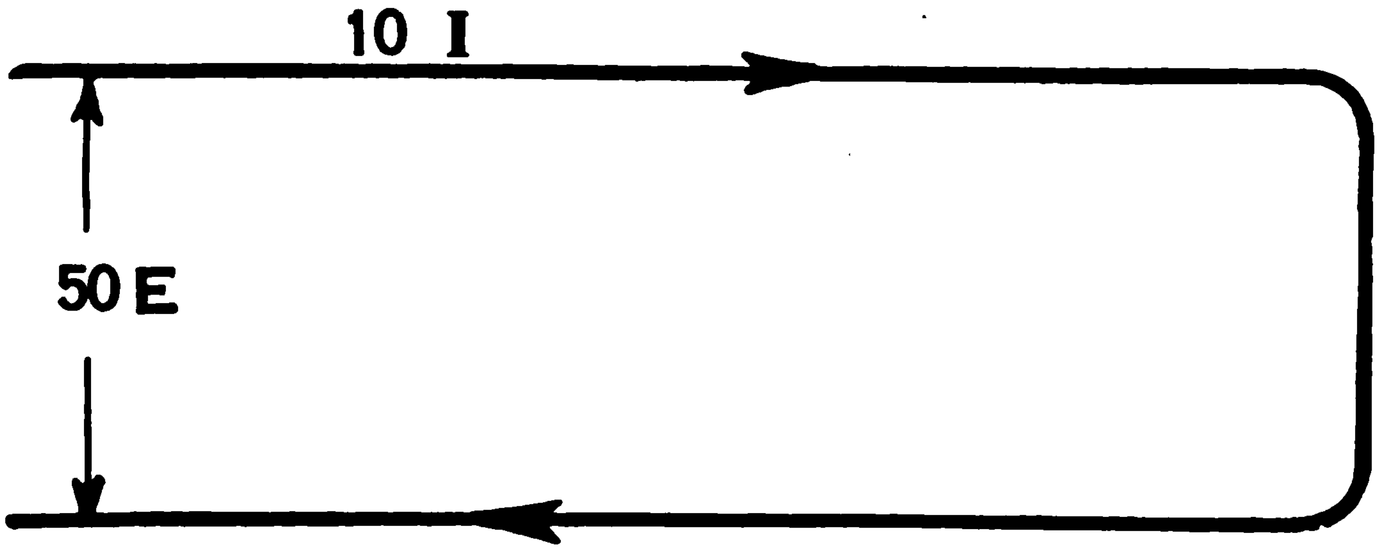


Fig. 1025

Thus if the complete circuit were 500 feet in length and the wire had a cross-section of 1,060 circular mils, the equation would be

$$\frac{10.6 \times 500}{1{,}060} = 5 \text{ ohms.}$$

As these are both expressions for the resistance of a wire, the two equations may be combined thus:

$$\frac{10.6 \times l}{c.m.} = \frac{E}{I}.$$

Transposing this expression for the value of the circular mils gives

$$\frac{10.6 \times l \times I}{E} = c.m.$$

Now substituting D for the distance one way between the source and the load in place of l and increasing the constant 10.6 to

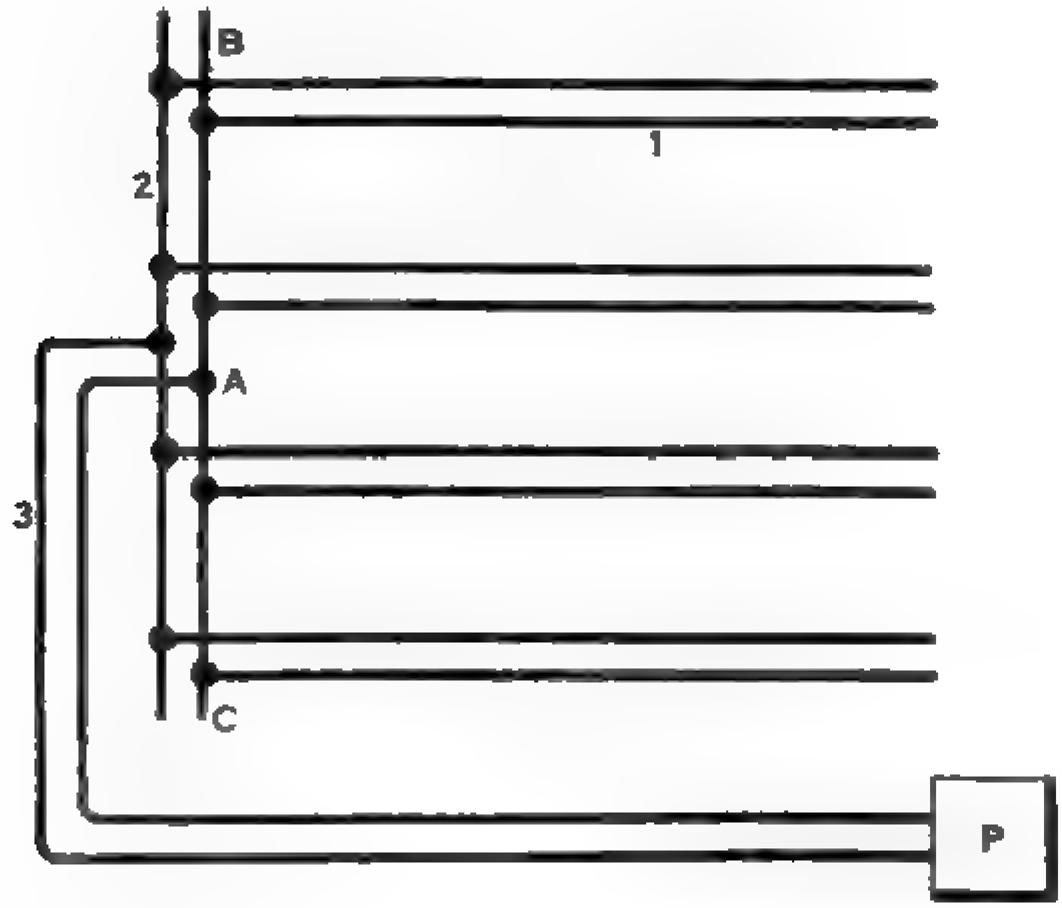


FIG. 1026.

11 to allow for increase in temperature and added resistance due to connections in the circuit, the expression becomes

$$\frac{11 \times 2 \times D \times I}{E} = c.m. = \frac{22 \times D \times I}{E} = c.m.$$

This is a standard equation for determining the size of wire for transmitting any direct current any distance with a given number of volts lost in the line.

Branch lines in houses are not usually more than 100 feet in length and are not permitted to carry over 660 watts. With this amount of power distributed on these circuits the loss in potential will rarely exceed one volt when using the smallest size wire permitted by the National Code, which is No. 14. It is therefore unnecessary to make a calculation to determine the

size of wire for branch lines, for the minimum size permitted is rarely less than a safe size. The length of mains in ordinary residences is usually so short that No. 10 or 12 wire will be amply large in the majority of cases without any calculation.

A check, however, should be made to be sure that the number of amperes assigned to the mains in any case does not exceed the safe carrying capacity prescribed for such wires in the National Code.

In wiring apartment houses, hotels, department stores and office buildings, the size of wire for branch lines and occasionally for mains may also be assigned in the same way as above. The feeder, however, which extends from a power plant, *P*, in the basement, as in Fig. 1026, to the center of distribution *A*, approximately midway between the top and bottom of the building, must be calculated with a prescribed loss of from 2 to 5% according to the load and the distance. The subfeeders which extend upward to *B* and downward to *C* should be sufficiently large to prevent the loss of more than 1 or 2 volts in each direction.

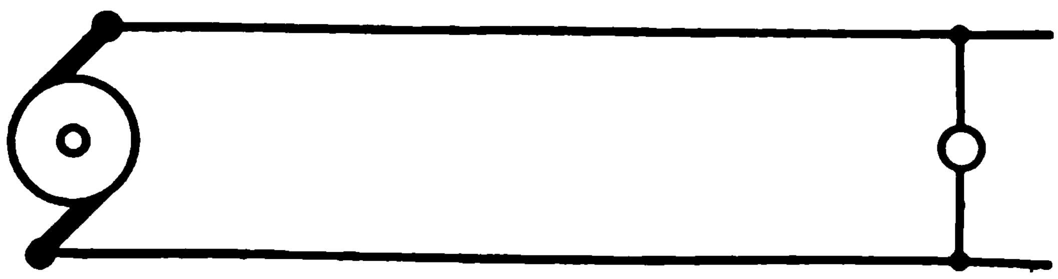


FIG. 1027.—Required, the size of wire to deliver 300 40-watt, 110-volt lamps, 500 feet, with 6% line loss.

A practical application of the above established formula will now be considered. Let it be required to deliver, at the point *A*, sufficient current to supply 300, 40-watt, 110-volt lamps from the power plant, *P*, the distance being 500 feet with an allowance of 6% for loss in the line. The circuit will be as represented in Fig. 1027. First the total current must be ascertained. This is found by multiplying the total number of lamps by the watts per lamp and dividing by the voltage at the lamps. Thus:

$$\frac{L \times P}{E} = I = \frac{300 \times 40}{110} = 109 \text{ amperes.}$$

100% represents the voltage at the generator.

6% is to be the loss in the line.

94% of the generator's voltage will reach the load and this

should be 110 volts. Therefore $\frac{110}{94\%} = 117$ volts at the generator. Deducting 110 volts at the lamps leaves 7 volts, which will be the actual loss in the line. Applying the formula to determine the size of the wire:

$$\frac{22 \times I \times D}{E} = \frac{22 \times 109 \times 500}{7} = 171{,}300 \text{ circular mils.}$$

The size of wire called for usually falls between two. gauge numbers. A safe rule is to take the next size larger wire. This, however, would often involve an unnecessary waste of copper. No. 0000 is considerably too large. In many instances it is entirely practical to take the next size smaller wire. This, however, would involve a somewhat larger number of volts lost. If, in the preceding case, No. 000 wire, which has 168,000 c.m., is substituted in the equation for the 7 volts lost, the quotient obtained would show the actual voltage lost with this slightly smaller wire.

Nothing but considerable experience will enable one to judge as to the most suitable loss to allow in a given case. If the prescribed **loss** is **high,** the **copper** required will be **small.** If the prescribed **loss** is **low,** the **copper** required will be **great.** Care should always be taken to check the size of wire called for in any case for interior wiring with the table giving the safe carrying capacity of wires in the National Electrical Code, and if this safe limit has been exceeded a smaller loss must be prescribed.

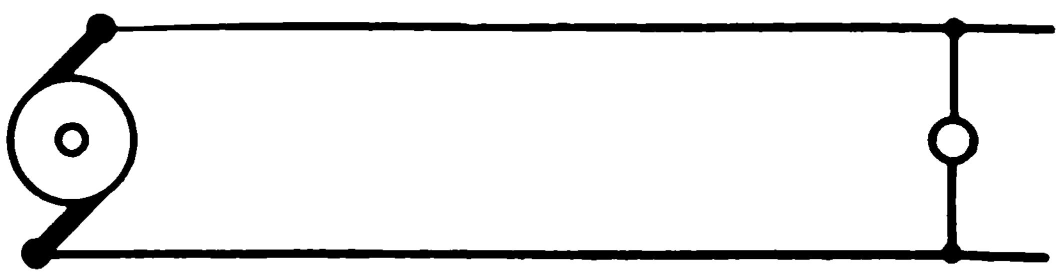


FIG. 1028.—Required, the size of wire to deliver 500 40-watt, 110-volt lamps, 400 feet, 120 volts at generator.

Sometimes the voltage is specified at the generating plant and also at the load, in which case the loss in the line which may be permitted can be determined by simply subtracting the received voltage from the generated volts. Consider a case in Fig. 1028, where 500, 40-watt, 110-volt lamps are to be operated

at a distance of 400 feet from a 120-volt generator. Obviously the loss in the line will be 120 volts minus 110 volts, or 10 volts. The current required by the lamps will be

$$\frac{L \times P}{E} = \frac{500 \times 40}{110} = 182 \text{ amperes.}$$

Applying the formula

$$\frac{22 \times I \times D}{E} = \text{c.m.} = \frac{22 \times 182 \times 400}{10} = 160{,}000 \text{ c.m.}$$

This is just a little less than the cross-section of a No. 000 wire, which will be of suitable size.

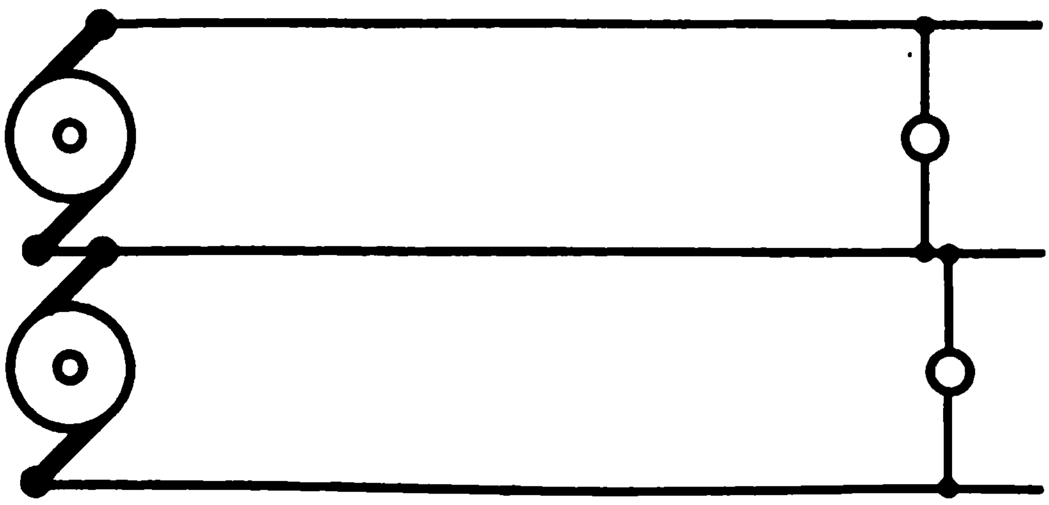


FIG. 1029.—Required, the size of wire to deliver 600 40-watt, 110-volt lamps, 800 feet, on the three-wire system, 236 volts at generator.

Next consider the application of the same formula to a three-wire circuit. Let it be required to supply 600 40-watt, 110-volt lamps at a distance of 800 feet from the generators, which supply 236 volts, Fig. 1029. The loss in the line is obviously 236 volts at the generator, minus 220 volts at the load, which equals 16 volts. Power is transmitted on a three-wire system at 220 volts instead of 110. Hence the current required will be

$$\frac{L \times P}{E} = I = \frac{600 \times 40}{220} = 109 \text{ amperes.}$$

Applying the formula:

$$\frac{22 \times I \times D}{E} = \text{c.m.} = \frac{22 \times 109 \times 800}{16} = 120{,}000 \text{ c.m.}$$

This will be the required cross-section for the positive and negative wires. The neutral wire in all such circuits where the load

is to be delivered at the end of the transmission line may safely be made one-half the size of the outside wires. Thus $\frac{120{,}000}{2} =$ 60,000 c.m. for the neutral wire. The B. & S. gauge corresponding will be No. 00 for the outside wires and No. 2 for the neutral.

It has been previously stated that the economy of a transmission line varies as the square of the voltage impressed. The foregoing formula may be used to prove this fact very clearly. Thus, let it be required to deliver 20,000 watts a distance of 5,000 feet with a loss of 5% in the line. First let the transmission be at 200 volts with 100 amperes. 5% of 200 volts equals 10 volts to be lost in the line. Applying the formula

$$\frac{22 \times I \times D}{E} = \frac{22 \times 100 \times 5{,}000}{10} = 1{,}100{,}000 \text{ c.m.}$$

Next consider the transmission of the same power the same distance with the same per cent loss but at 2,000 volts and therefore requiring only 10 amperes. 5% of 2,000 volts equals 100 volts lost in the line.

$$\frac{22 \times I \times D}{E} = \text{c.m.} = \frac{22 \times 10 \times 5{,}000}{100} = 11{,}000 \text{ c.m.}$$

It will be observed that, in this case, the result of making the transmitting voltage 10 times as great has been to reduce the current required to 1/10 of the former amount and increase the actual voltage lost to 10 times the former amount. This reduces the numerator in the equation to 1/10 its former value and increases the denominator 10 times. The quotient is therefore 1/100 the amount obtained in the first case. Thus, increasing the voltage of transmission for a given amount of power to 10 times the initial value reduces the copper required to 1/100.

Circular Mil Formula for Aluminum Wire.—The circular mil formula may be adapted for finding the size of wire of any material by substituting for the constant 22, which is the resistance of one circuit foot of copper of one circular mil cross-section, the resistance of one circuit foot of any other conductor of one circular mil cross-section. The cross-section of an aluminum wire must bear the relation of 159 to 100 when compared with copper wire. Therefore the circular mils of an aluminum wire must be 1.59 times the circular mils of a copper wire of equal

conductivity. Therefore the constant 22 may be multiplied by 1.59, which will give 35. The formula for obtaining the size of an aluminum wire for any installation will then be:

$$\frac{35 \times I \times D}{E} = \text{c.m. aluminum.}$$

Weight Formula for Copper Wire.—It so happens that 1,000 feet of copper wire of 1,000 c.m. cross-section weighs 3 pounds. If, then, in the equation for circular mils, $\frac{22 \times I \times D}{E} = \text{c.m.}$, 3 be placed in the numerator and 1,000 in the denominator, the quotient will be the "pounds per thousand feet" instead of the circular mils. Thus

$$\frac{3 \times 22 \times I \times D}{1{,}000 \times E} = \text{pounds per thousand feet.}$$

By writing the distance one way, in "thousands of feet," as *Dm* in place of *D*, and by combining the two constants in the numerator, the expression becomes $\frac{66 \times I \times Dm}{E}$ = pounds per thousand feet. If this expression for the weight in pounds per thousand feet is multiplied by *Dm*, which is the distance one way from the generator to the load, and again by 2, to give the total distance out and back, the result will be an expression for the total weight of copper for the entire circuit. Thus $\frac{66 \times I \times Dm}{E} \times Dm \times 2 = \frac{132 \times I \times Dm^2}{E}$ = total number of pounds required.

B. & S. Gauge Formula for Copper Wire.—A simpler formula for determining the size of wire for direct-current installations which obviates the necessity for referring to a wire table to find the gauge number corresponding to a given circular milage is as follows:

$$\frac{I \times D}{E} = K. \qquad \frac{K}{16} = \text{pounds per thousand feet.}$$

Where: I = current in amperes.
D = distance one way to load.
E = volts lost in line.
K = gauge number factor.
16 = constant.

As an example of the application of this formula, consider the determination of the size of wire required to transmit power to a 12-ampere, 220-volt motor, situated 1,500 feet away from a 230-volt generator. The loss in the line will be 230 minus 220 or 10 volts. Applying the formula

$$\frac{I \times D}{E} = \frac{12 \times 1{,}500}{10} = 1{,}800 \text{ gauge number factor.}$$

The corresponding gauge number may be found in the accompanying table:

Size of wire B. & S. gauge	K	Size of wire B. & S. gauge	K
0000	10,400	6	1,300
000	8,000	7	1,000
00	6,400	8	800
0	5,200	9	650
1	4,000	10	500
2	3,200	11	400
*3	2,600	12	325
*4	2,000	13	250
*5	1,600	14	200

The nearest size wire corresponding to a factor of 1,800 is No. 4, which has a factor of 2,000. This factor happens to be the weight of copper in ounces per one thousand feet. To find the weight in pounds apply the formula, $\frac{K}{16}$ = pounds per thousand feet. Thus $\frac{2{,}000}{16} = 125$ pounds per thousand feet. The distance one way is 1,500 feet. The total length required out and back is D times 2 or 3,000 feet. In this case the total weight will be 125 pounds per thousand feet, times 3, or 375 pounds. If bare copper costs 20 cents per pound, the total cost for the installation would be $75.

A study of the table will show that the combination upon which the factors are based can be very easily remembered. These factors are proportional, in round numbers, to the circular mils. In fact any constant multiplied by 22 will be approxi-

mately the circular milage of the corresponding wire. Starting with any particular factor and going up toward the larger sizes, it will be observed that the factor for every third size is halved. By remembering the factor for three gauge numbers such as numbers 3, 4 and 5*, it is a simple matter to build the table up or down toward the size of the particular wire called for in the calculation. The formula is so easily remembered and the relation between the factors so simple that one can readily carry the entire combination in the head and make calculations for interior wiring with very satisfactory results without any other source of information.

As the size of wire called for usually falls between two gauge numbers, it is often necessary to take a wire either too large or too small. A little study of the table will show, however, that a combination of two or more wires of the same or different sizes will often give the exact cross-section required. Thus in the preceding example, a No. 7 having a factor of 1,000, and a No. 8 with a factor of 800, would have an aggregate carrying capacity equal to the sum of these two, which equals the 1,800 factor called for in the problem. While it would not be desirable to use two insulated wires tied together in parallel for inside wiring, a bare No. 7 and No. 8 could be very readily tied to the same pin in an outside line in place of a No. 4. This combining of wires of various sizes can be carried out as far as desired; thus ten No. 8 wires, having a factor of 800, would have an aggregate capacity of one No. 000, whose factor is 10 times 800 or 8,000, while four No. 7 wires, with a factor of 1,000, would equal a No. 1, whose factor is 4,000.

SECTION XIX CHAPTER III

TRANSMISSION OF POWER

CALCULATION OF TRANSMISSION LINES

1. How much power should be lost in heat in a transmission line?
2. What three factors enter into the determination of a suitable loss to allow in a transmission line?
3. What is the "diversity factor" in a power load? How does it influence the permissible loss in a transmission line?
4. What effect has the per cent of loss allowed in the line, upon the ~~ulation of the system and the range of voltage to which the lamps motors may be subjected under variation in load?

5. Required: The size of wire to deliver 200 40-watt, 110-volt lamps, 400 feet, with 5 per cent of the generated voltage lost in the line.

6. Required: The size of wire in circular mils to deliver 400, 40-watt, 110-volt lamps, 300 feet, with 6 per cent of the generated voltage lost in the line.

7. Required: The size of wire to deliver 350 40-watt, 110-volt lamps, 500 feet, with 118 volts at generator.

8. Required: The size of wire to deliver 275 40-watt, 112-volt lamps 300 feet, with 116 volts at generator.

9. Required: The size of wire in circular mils for positive, negative and neutral to deliver 500 40-watt, 110-volt lamps 1,000 feet on the three-wire system, with 238 volts at the generator?

10. Required: The size of wire in circular mils for positive, negative and neutral to deliver 300 40-watt, 110-volt lamps, 750 feet on the three-wire system, 234 volts at the generator.

11. Required: The size of aluminum wire in circular mils to transmit 200 k.w. under a pressure of 2,000 volts at the power station, a distance of 5,000 feet with a loss of 10 per cent of the generated voltage in the transmission line.

12. Required: The size of copper wire, B. & S. gauge, by the constant table to transmit 16 amperes to a 500-volt motor 5,000 feet away from a railway generator delivering 550 volts.

13. Required: The size of copper wire, B. & S. gauge, by the constant table to deliver 250 40-watt, 110-volt lamps, 350 feet from the generator; allow 5 per cent of generated voltage to be lost in the line.

14. Required: The size of positive, negative and neutral wires, B. & S. gauge by the constant table to deliver 450 40-watt, 110-volt lamps 800 feet on the three-wire system, 235 volts at the generator.

TRANSMISSION OF POWER

ALTERNATING-CURRENT TRANSMISSION

It is more difficult to calculate the size of wire for alternating current than for direct current installations for the following reasons: With direct-current, a certain loss is prescribed. If the calculated size of wire is used, the stated loss will occur.

In an A.C. transmission a certain loss may be prescribed, but that loss is the ohmic drop only. The transmission line will involve a reactive drop in addition, which depends upon the current, the size of the wires and the spacing between them. As the reactive drop cannot be ascertained until the size of wire is known, and as the size of wire necessary cannot be determined without knowing the total drop which is to occur therein, the difficulties encountered can be readily appreciated.

Furthermore, in a direct-current system, the amount of current required to deliver a given power at fixed voltage is always the same. In an A.C. transmission the current required increases as the power factor decreases.

In a D.C. transmission the total **voltage** lost in the line determines the **power** lost in the line and the voltage lost measures the regulation. In an A.C. transmission the **energy** lost in the line is determined by its **resistance** while the **regulation** of the line is determined by the **impedance** drop which is the vector sum of the resistance drop and the reactive drop.

Single-Phase Calculation.—In the following problems these factors will be taken into account and the various methods of approaching different problems will be considered in detail. In the first place assume a transmission line in which the following data is given:

Power at the load, 5,000 K.W.
Distance of transmission, 20 miles.
Nominal line voltage, 33,000.
Frequency, 60 cycles.
Power factor of the load, 85%.

Line loss, 10% of watts generated.

Spacing of wires, 48 inches between centers.

Assumed voltage regulation, 19%.

The voltage stated is the nominal voltage at the source which will fall from this value at the receiving end. The regulation that is assumed is arbitrarily established and can be subsequently altered if the calculations do not bear out the assumed value. The layout is as shown in Fig. 1009. The alternator generates 6,600 or 11,000 volts and by means of raising transformers, *T*, delivers approximately 33,000 volts.

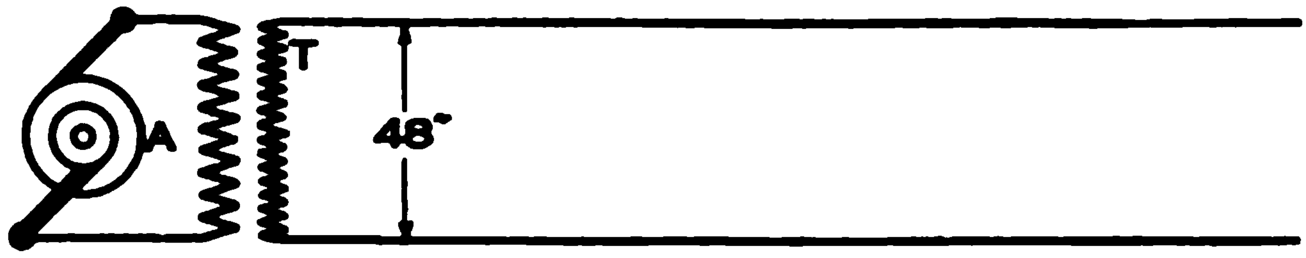


FIG. 1030.—Required, the size of wire to deliver 5,000 K.W., 20 miles with 10% line loss; power factor 85%, frequency 60 cycles, nominal voltage of transmission 33,000; spacing between wires 48".

Calculation:

$$\text{Volts at receiving end of line} = \frac{33{,}000}{1.19} = 27{,}740 \text{ volts.}$$

$$\text{Amperes per wire} = \frac{\mathrm{P}}{E \times \cos.\Phi} = I = \frac{5{,}000{,}000}{27{,}740 \times 0.85} =$$

212 amperes.

Ten per cent of 5,000 K.W. equals 500 K.W. This is the loss in terms of delivered power. Dividing this amount by 0.90 gives the loss in terms of generated power. Thus $\frac{500}{0.90} = 556$ K.W. Dividing this amount by 2 gives 278 K.W. lost in each wire.

$$I^2R = P \text{ (lost) } \frac{P}{I^2} = R \text{ (for one wire).}$$

$$\frac{278{,}000}{212^2} = 6.18 \text{ ohms resistance for 20 miles.}$$

$$\frac{6.18}{20} = 0.309 \text{ ohm per mile.}$$

From the following table No. 000 wire will be found to possess a resistance of 0.336 ohm per mile. The resistance for 20 miles is $0.336 \times 20 = 6.72$ ohms.

RESISTANCE IN OHMS PER MILE FOR COPPER AND ALUMINUM WIRE. ALUMINUM 61% CONDUCTIVITY

Aluminum c.m.	Resistance at 68° F.	Size equivalent copper, 97% cond.
795,500	0.1127	500,000 c.m.
715,500	0.1254	450,000
636,000	0.1409	400,000
556,500	0.1611	350,000
477,000	0.1879	300,000
397,500	0.2253	250,000
336,420	0.2667	No. 0000 B. & S.
266,800	0.3360	000
211,950	0.4229	00
167,800	0.5342	0
133,220	0.6720	1
105,530	0.8486	2
83,840	1.071	3
66,370	1.350	4
52,630	1.703	5
41,740	2.147	6

From the following table the reactance of No. 000 is found to be 0.692 ohm per mile for a spacing of 48 inches between wires at a frequency of 60 cycles.

The reactance for 20 miles in $0.692 \times 20 = 13.84$ ohms.

In the following formulas the voltage at the generator is estimated by combining the energy and wattless components of the voltage at the load and adding these vectorily with the energy and wattless components of the voltage lost in the line. Thus,

$$Eg = \sqrt{(El \cos. \Phi + IR)^2 + (El \sin. \Phi + IX)^2}$$

Where:

Eg = generated volts.
El = received volts.
$\text{Cos}\, \Phi \times 100$ = power factor.
IR = resistance drop.
IX = reactance drop.

Fig. 1031 shows the vector for this calculation. With a power factor of 85% at the load, the energy component is found

MAGNETIC REACTANCE IN OHMS PER MILE AT 60 CYCLES

Circular mils stranded	Spacing in inches between wires.										
	12	18	24	36	48	60	72	84	96	108	120
500,000	0.451	0.500	0.535	0.584	0.619	0.647	0.669	0.688	0.703	0.718	0.730
450,000	0.458	0.506	0.541	0.591	0.625	0.653	0.675	0.693	0.709	0.724	0.736
400,000	0.464	0.514	0.548	0.598	0.632	0.660	0.682	0.700	0.716	0.731	0.743
350,000	0.472	0.522	0.556	0.606	0.640	0.668	0.690	0.708	0.724	0.739	0.751
300,000	0.482	0.532	0.566	0.615	0.650	0.677	0.699	0.718	0.734	0.748	0.760
250,000	0.493	0.542	0.577	0.626	0.661	0.688	0.711	0.729	0.745	0.759	0.772
B. & S. solid											
0000	0.510	0.558	0.594	0.642	0.677	0.704	0.726	0.746	0.762	0.776	0.788
000	0.524	0.572	0.608	0.656	0.692	0.718	0.740	0.760	0.776	0.790	0.802
00	0.538	0.586	0.622	0.670	0.706	0.732	0.754	0.774	0.790	0.804	0.816
0	0.552	0.600	0.636	0.684	0.720	0.746	0.768	0.788	0.804	0.818	0.830
1	0.566	0.614	0.649	0.698	0.734	0.760	0.782	0.802	0.818	0.832	0.844
2	0.580	0.628	0.664	0.712	0.748	0.774	0.796	0.816	0.832	0.846	0.858
3	0.594	0.642	0.678	0.726	0.762	0.788	0.810	0.829	0.846	0.860	0.872
4	0.608	0.657	0.692	0.740	0.776	0.803	0.824	0.843	0.860	0.874	0.886
5	0.622	0.671	0.706	0.754	0.790	0.817	0.838	0.858	0.874	0.888	0.900
6	0.636	0.684	0.720	0.768	0.804	0.831	0.853	0.872	0.888	0.902	0.915

MAGNETIC REACTANCE IN OHMS PER MILE AT 25 CYCLES

Circular mils stranded	Spacing in inches between wires.										
	12	18	24	36	48	60	72	84	96	108	120
500,000	0.188	0.208	0.223	0.243	0.258	0.269	0.279	0.287	0.293	0.299	0.304
450,000	0.191	0.211	0.226	0.246	0.261	0.272	0.281	0.289	0.296	0.301	0.307
400,000	0.194	0.214	0.229	0.249	0.264	0.275	0.284	0.292	0.299	0.305	0.310
350,000	0.197	0.217	0.232	0.252	0.267	0.278	0.288	0.296	0.302	0.308	0.313
300,000	0.201	0.221	0.236	0.256	0.271	0.284	0.291	0.299	0.306	0.311	0.317
250,000	0.206	0.226	0.241	0.261	0.275	0.287	0.296	0.304	0.310	0.316	0.321
B. & S. solid											
0000	0.212	0.233	0.247	0.268	0.282	0.293	0.303	0.311	0.318	0.323	0.328
000	0.218	0.239	0.253	0.273	0.288	0.299	0.309	0.316	0.323	0.329	0.334
00	0.224	0.244	0.259	0.279	0.294	0.305	0.314	0.322	0.329	0.335	0.340
0	0.230	0.250	0.265	0.285	0.300	0.311	0.320	0.328	0.335	0.341	0.346
1	0.236	0.256	0.271	0.291	0.306	0.317	0.326	0.334	0.341	0.346	0.352
2	0.242	0.262	0.277	0.297	0.312	0.323	0.332	0.340	0.347	0.352	0.358
3	0.248	0.268	0.283	0.302	0.318	0.329	0.338	0.346	0.352	0.358	0.364
4	0.253	0.274	0.288	0.308	0.324	0.335	0.344	0.351	0.358	0.364	0.370
5	0.259	0.280	0.294	0.314	0.330	0.340	0.350	0.357	0.364	0.370	0.376
6	0.265	0.285	0.300	0.320	0.335	0.346	0.356	0.363	0.370	0.376	0.381

TABLE GIVING AREA, DIAMETER, WEIGHT AND RESISTANCE OF BARE, COTTON-COVERED AND ENAMELED COPPER WIRE.

B. & S. gauge	Diam. mils bare	Cross-sectional area		Diameter over insulation				Per 1000 feet				
									Ohms			
		Circular mils	Square mils	Single-cotton	Double-cotton	Triple-cotton	Enamel	Pounds bare	20°	40°	75°	100°
0000	460	212000	166000	....	....	....	....	640	0.0491	0.0529	0.0597	0.0645
000	410	168000	132000	....	....	....	....	509	0.0617	0.0665	0.0751	0.0811
00	365	133000	105000	....	....	....	....	405	0.0776	0.0837	0.0944	0.102
0	325	106000	83000	....	339	343	....	320	0.0981	0.106	0.119	0.129
1	289	83500	65600	....	303	307	....	253	0.124	0.134	0.151	0.163
2	258	66600	52300	....	272	276	....	202	0.156	0.168	0.189	0.205
3	229	52400	41200	....	242	247	....	159	0.198	0.213	0.240	0.260
4	204	41600	32700	211	216	220	....	126	0.249	0.269	0.303	0.328
5	182	33100	26000	189	194	198	....	100	0.313	0.338	0.381	0.412
6	162	26200	20600	169	174	178	....	79.4	0.395	0.426	0.481	0.520
7	144	20700	16300	151	156	160	....	62.8	0.500	0.539	0.608	0.657
8	129	16600	13100	136	141	145	133	50.5	0.622	0.671	0.756	0.818
9	114	13000	10200	121	126	130	118	39.3	0.799	0.861	0.971	1.05
10	102	10400	8170	108	112	116	105	31.5	0.997	1.08	1.21	1.31
11	91	8280	6500	97	101	105	94	25.1	1.25	1.35	1.52	1.65
12	81	6560	5150	87	91	95	84	19.9	1.58	1.71	1.92	2.08
13	72	5180	4070	78	82	86	75	15.7	2.00	2.16	2.43	2.63
14	64	4100	3220	70	74	78	67	12.4	2.53	2.73	3.08	3.33
15	57	3250	2550	63	67	71	60	9.83	3.19	3.44	3.89	4.20
16	51	2600	2040	56	59	63	53.5	7.86	3.99	4.31	4.86	5.25

TABLE GIVING AREA, DIAMETER, WEIGHT AND RESISTANCE OF BARE, COTTON-COVERED AND ENAMELED COPPER WIRE—Contd.

B. & S. gauge	Diam. mils bare	Cross-sectional area		Diameter over insulation				Per 1000 feet				
									Ohms			
		Circular mils	Square mils	Single-cotton	Double-cotton	Triple-cotton	Enamel	Pounds bare	20°	40°	75°	100°
17........	45	2030	1590	50	53	57	47.5	6.13	5.12	5.52	6.23	6.74
18........	40	1600	1260	45	48	52	42	4.86	6.46	6.97	7.86	8.50
19........	36	1300	962	39	43	47	37	3.71	8.47	9.13	10.3	11.1
20........	32	1020	804	36	40	44	34	3.10	10.1	10.9	12.3	13.3
21........	28.5	812	638	32.5	36.5	40.5	30.5	2.46	12.8	13.8	15.5	16.8
22........	25.5	650	511	29.5	33.5	37.5	27.5	1.97	15.9	17.2	19.4	21.0
23........	23	529	415	27	31	35	25	1.60	19.6	21.2	23.9	25.8
24........	20	400	314	24	28	32	22	1.21	25.9	28.0	31.6	34.1
25........	18	324	254	22	26	....	20	0.979	32.1	34.6	39.0	42.2
26........	16	256	201	20	24	....	17.5	0.775	40.5	43.7	49.3	53.3
27........	14	196	154	18	22	....	15.5	0.594	52.9	57.0	64.3	69.5
28........	12.6	159	125	16.6	20.6	....	14	0.482	65.2	70.3	79.3	85.7
29........	11	121	95	15	19	....	12	0.366	82	92.4	100	113
30........	10	100	78.5	14	18	....	11	0.303	104	112	126	136
31........	9	81	63.6	13	17	....	10	0.245	128	138	156	168
32........	8	64	50.3	12	16	....	8.9	0.194	162	175	197	213
33........	7	49	38.5	11	15	....	7.9	0.148	207	228	252	278
34........	6.3	39.7	31.2	10.3	14.3	....	7.1	0.120	261	282	318	343
35........	5.6	31.4	24.6	9.6	13.6	....	6.4	0.095	331	357	403	435
36........	5	25	19.6	8.5	12	....	5.7	0.076	415	448	505	546

by multiplying A-C, 27,740 volts, at the receiving end, by 85%, which gives A-B, which equals 23,579 volts. The wattless component B-C is obtained by multiplying A-C, 27,740 volts, by the sine of Φ, which is 0.527, giving B-C, 14,618 volts. To the received voltage A-C must be added the line drop C-E, to determine the voltage A-E, which must be supplied by the generator. The ohmic drop in the line C-D is found by multiplying the line current, 212 amperes, by the resistance of the line. Each wire has a resistance of 6.72 ohms. The two wires will therefore

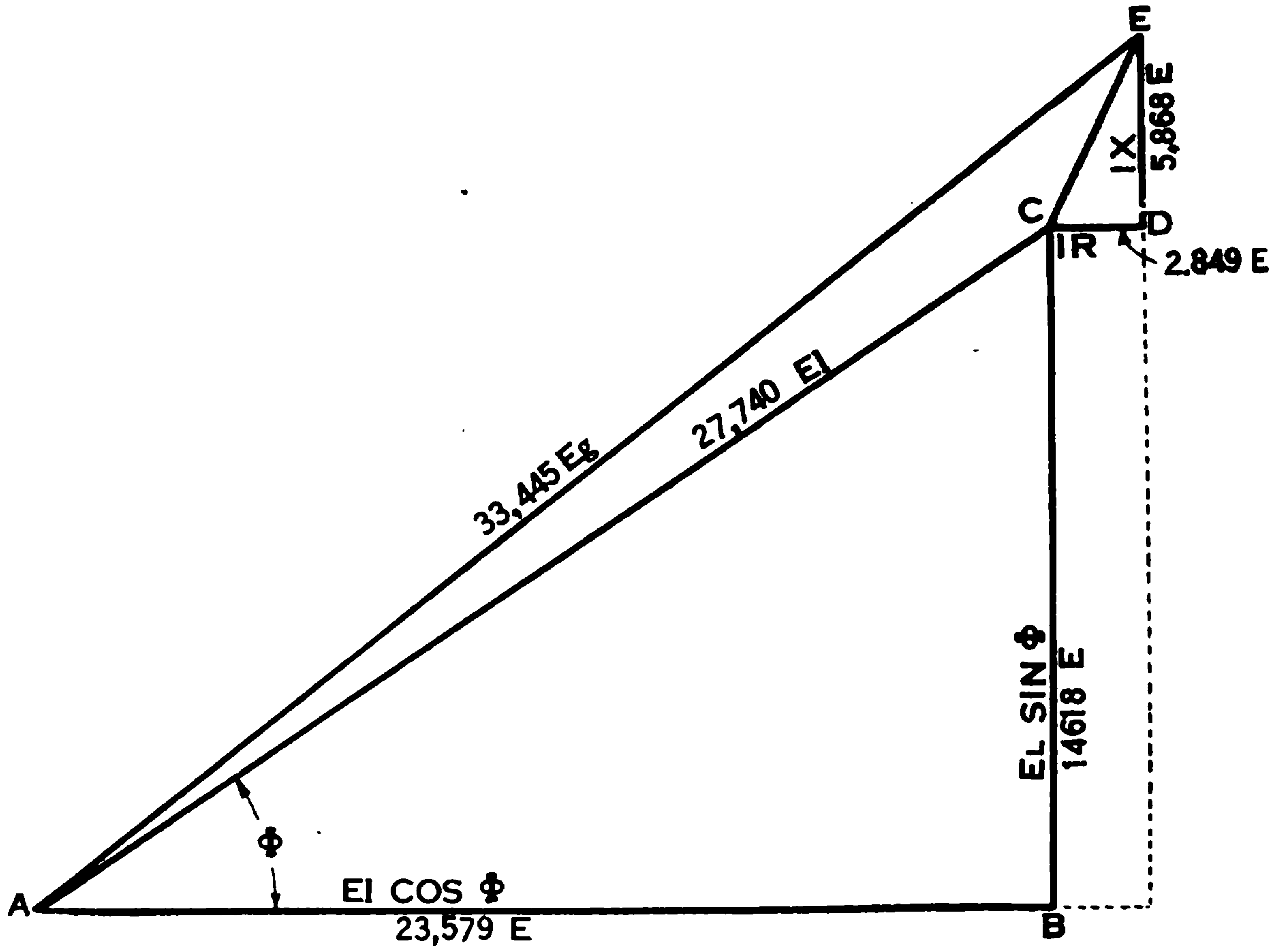


FIG. 1031.

have a resistance of 13.44 ohms. This resistance multiplied by 212 amperes gives 2,849 volts ohmic drop. The reactive drop in the line, D-E, is found by multiplying this same current, 212 amperes, by the total reactance of the circuit. This was 13.84 ohms for one wire or 27.68 ohms for both. This reactance multiplied by 212 amperes gives 5,868 volts reactive drop. Substituting these values in the equation gives:

$$Eg = \sqrt{(27{,}740 \times 0.85) + (212 \times 13.44)^2 + (27{,}740 \times 0.527) + (212 \times 27.68)^2}$$

Eg = 33,445 volts.

$\frac{Eg - El}{El} \times 100 = \text{per cent regulation} = \frac{33{,}445 - 27{,}740}{27{,}740} \times 100 = 20.3$ per cent regulation.

This checks closely with the assumed 19.0 per cent.

In three-phase calculations it is usual to figure each wire of the circuit independently as the circuit is not a simple one. By calculating the voltage of the line from each conductor to an assumed neutral and substituting this value in the formula together with the current, resistance and reactance of a single wire, the problem compares with single-phase calculations as regards simplicity.

A convenient way of looking at the single-phase calculations is to remember that the load on the generator consists of two units, one the line itself and the other the load connected at the point under consideration. The problem then becomes similar in solution to two impedances in series. The foregoing example can be reduced to a calculation of one wire with the result that

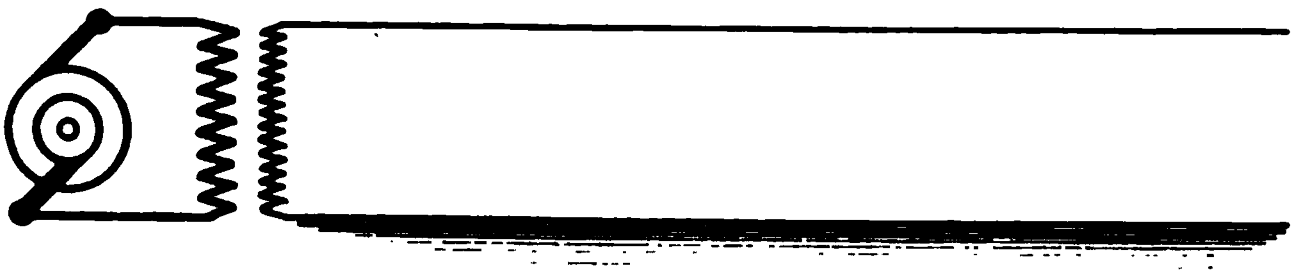


FIG. 1032

the regulation is found to be the same as with two wires. Assume the return circuit to be grounded, as in Fig. 1032, and the outgoing line to simply involve one-half of the resistance and one-half the reactance, formerly included in the calculation. The return wire will be assumed to have zero resistance and reactance. Applying the formula gives the following result:

$$Eg = \sqrt{\overline{(13{,}870 \times 0.85) + (212 \times 6.72)}^2 + \overline{(13{,}870 \times 0.527) + (212 \times 13.84)}^2}$$

$Eg = 16{,}690$. This is just one-half of 33,445. Using these values, the regulation is almost exactly 20.3%, as before.

In the preceding example the nominal voltage at the source was assumed. The required voltage at the load was calculated based upon a resistance loss in the line. To this delivered voltage the resistance loss and the reactive drop were vectorily

added. This gave a somewhat larger voltage at the source than the nominal voltage assumed. It was necessary to assume a certain regulation, and the actual regulation resulting differed somewhat from the assumed values.

Three-Phase Calculation.—The calculation of the size of wire for a three-phase transmission line will now be considered.

Let the requirements of the problem be as follows:

Power at the load, 5,000 h.p.
Distance of transmission, 5 miles.
Volts at the load, 6,600.
Frequency, 60 cycles.
Power factor of the load, 95%.
Watts lost in the line, 10% of watts at generator.
Spacing of wires, 18 inches between centers.

The lay-out of this circuit is shown in Fig. 1033. Here the voltage at the load is given as a starting point. Based upon a

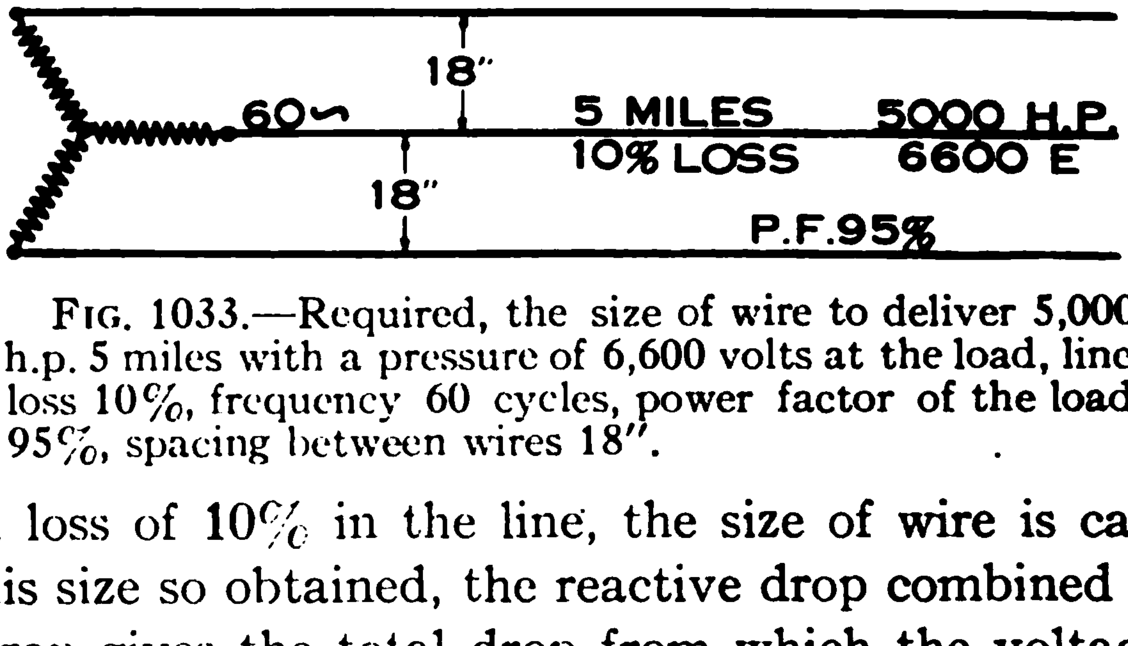


FIG. 1033.—Required, the size of wire to deliver 5,000 h.p. 5 miles with a pressure of 6,600 volts at the load, line loss 10%, frequency 60 cycles, power factor of the load 95%, spacing between wires 18".

specified loss of 10% in the line, the size of wire is calculated. From this size so obtained, the reactive drop combined with the ohmic drop gives the total drop from which the voltage at the source is computed and the regulation ascertained. This eliminates the necessity of assuming a nominal voltage to begin with and an approximation of the regulation in the line. The calculation is as follows:

$$5{,}000 \times 746 = 3{,}730 \text{ K.W.}$$

$$\frac{3730}{3} = 1{,}243.3 \text{ K.W. per phase.}$$

$$\text{Volts from each wire to the neutral} = \frac{6600}{\sqrt{3}} = 3{,}810 \text{ volts.}$$

With 1,243.3 K.W. per phase and the power factor 95%, the amperes per wire will be;

$$\frac{\text{K. W.} \times 1{,}000}{E \times \cos.\ \Phi} = \frac{1{,}243.3 \times 1{,}000}{3{,}810 \times 0.95} = \text{342 amperes (approximately).}$$

If 10% of the generated watts are lost in the line, 90% of the generated watts must be delivered at the load. The watts at the station bus will therefore be:

$$\frac{3{,}730}{0.90} = 4{,}144.4 \text{ K.W.}$$

If 4,144.4 K.W. are delivered to the bus and 3,730 K.W. delivered at the load, the watts lost in the line will be the difference between these two quantities.

$$4{,}144.4 - 3{,}730 = 414.44 \text{ K.W. lost in line.}$$

As this loss is equally distributed between three conductors in the line, the loss per wire will be:

$$\frac{414.44}{3} = 138.1 \text{ K.W.}$$

$$\frac{P}{I^2} = R.$$

Therefore:

$$\frac{138.1 \times 1{,}000}{342^2} = 1.18 \text{ ohms, resistance of one wire.}$$

As the line is 5 miles long, the resistance per mile will be:

$$\frac{1.18}{5} = 0.236 \text{ ohm.}$$

Referring to the table of resistance of copper wire, page 405, the nearest commercial size is 250,000 c.m. cable, which has a resistance of 0.2253 ohm per mile. This is lower than the required value but will improve the regulation of the line. Using this size cable, the resistance of a 5-mile line will be:

$$0.2253 \times 5 = 1.1265 \text{ ohms.}$$

Referring to the table of inductive reactance on page 406 for 250,000 c.m. cable, spaced 18 inches between centers, the reactance is found to be 0.542 ohm per mile for 60 cycles. The total inductive reactance for the 5-mile line will be:

$$0.542 \times 5 = 2.71 \text{ ohms}$$

Using the same fundamental formula as in the preceding problem and substituting the above values:

$$Eg = \sqrt{\overline{(3{,}810 \times 0.95) + (342 \times 1.127)}^2 + \overline{(3{,}810 \times .312) + (342 \times 2.71)}^2}$$

Eg = 4,534 volts generated between the neutral and each line conductor.

The vector is shown in Fig. 1034, which is in every way similar to 1010 except that the reactive drop in the line is relatively greater and the power factor of the load is relatively better.

The volts between line wires at the generator will be:

$$4{,}534 \times \sqrt{3} = 7{,}850 \text{ volts.}$$

The regulation of the line expressed in terms of delivered voltage will be:

$$\frac{Eg - El}{El} \times 100 = \frac{7{,}850 - 6{,}600}{6{,}600} \times 100 = 19\%.$$

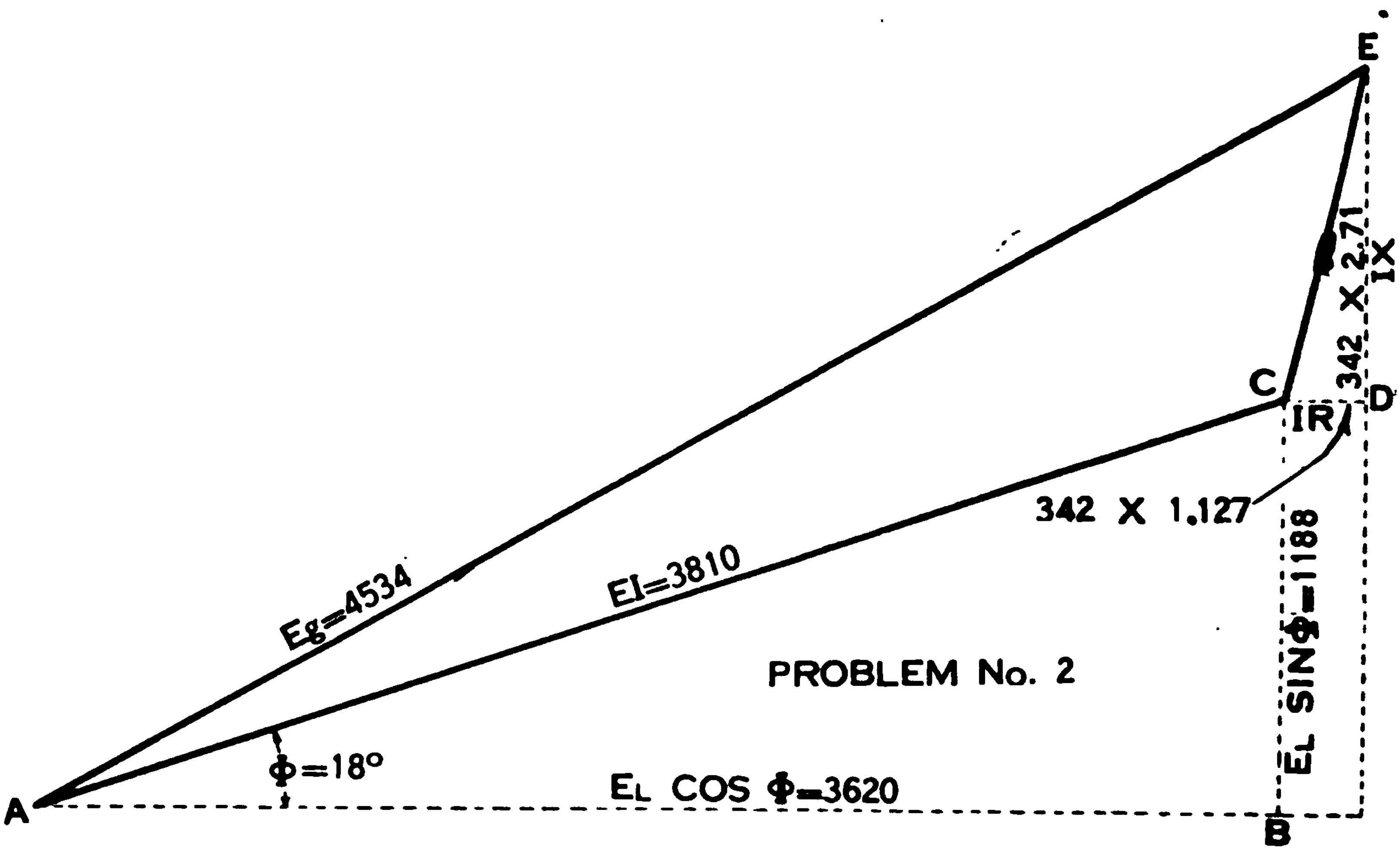


FIG. 1034.

Three-Phase Calculation for Long Line and High Voltage.—On short lines at moderate voltages the capacity effect of the circuit is so small that it may be neglected as a factor in the regulation of the line. On long lines at high voltages, with a lagging power factor, the charging current in the line may be sufficient to slightly improve the power factor. The effect of capacity in such a circuit will be now considered in a problem. The conditions are as follows:

Three-phase system:

Power at the load, 10,000 K.W.

Distance, 90 miles.

Voltage at the load, 66,000.
Frequency, 25 cycles.
Power factor of the load, 80%.
Watts lost in the line, 10% of generated watts.
Spacing of wires, 96 inches between centers.

The lay-out of this circuit is shown in Fig. 1035. The voltage at the receiving end is given as before, and no adjustment of voltage

FIG. 1035.—Required, the size of wire to deliver 10,000 K.W. 90 miles, 66,000 volts at the load, 10% line loss, power factor 80%, frequency 25 cycles.

at the source need be assumed in advance. The calculations are as follows:

$$\frac{10{,}000}{3} = 3{,}333.33 \text{ K.W. per phase.}$$

$$\frac{66{,}000}{\sqrt{3}} = 38{,}100 \text{ volts to neutral.}$$

$$\frac{\text{K.W.} \times 1000}{E \times \cos.\ \Phi} = I = \frac{3{,}333.3 \times 1{,}000}{38{,}100 \times 0.80} = 109.15 \text{ amperes per wire.}$$

If 10% of the generated watts is lost in the line, 90% of the watts at the generator must be delivered at the load.

$$\frac{10\,000}{0.90} = 11{,}111 \text{ K.W. at generator bus.}$$

11,111 K.W. generated minus 10,000 K.W. delivered at load equals 1,111 K.W. lost in the line. As this loss is equally distributed between three conductors the loss per conductor will be:

$$\frac{1{,}111}{3} = 370.3 \text{ K.W.}$$

As in the preceding problem, the resistance of each line wire will be:

$$\frac{P}{I^2} = R = \frac{370.3 \times 1{,}000}{109.15^2} = 30.9 \text{ ohms.}$$

Since the line is 90 miles long, the ohms per mile will be:

$$\frac{30.9}{90} = 0.344.$$

From a table of resistance of copper wire, page 405, the nearest commercial size is No 000 which has a resistance of 0.336 ohm per mile.

The resistance of 90 miles of No. 000 wire is:

$$0.336 \times 90 = 30.24 \text{ ohms.}$$

From the table of inductive reactance, page 407, No. 000 solid conductor, spaced 96 inches between centers, 25 cycles, is 0.323 ohm per mile. The total reactance for 90 miles is:

$$0.323 \times 90 = 29.07 \text{ ohms.}$$

The vector for this circuit is shown in Fig. 1036. Here the

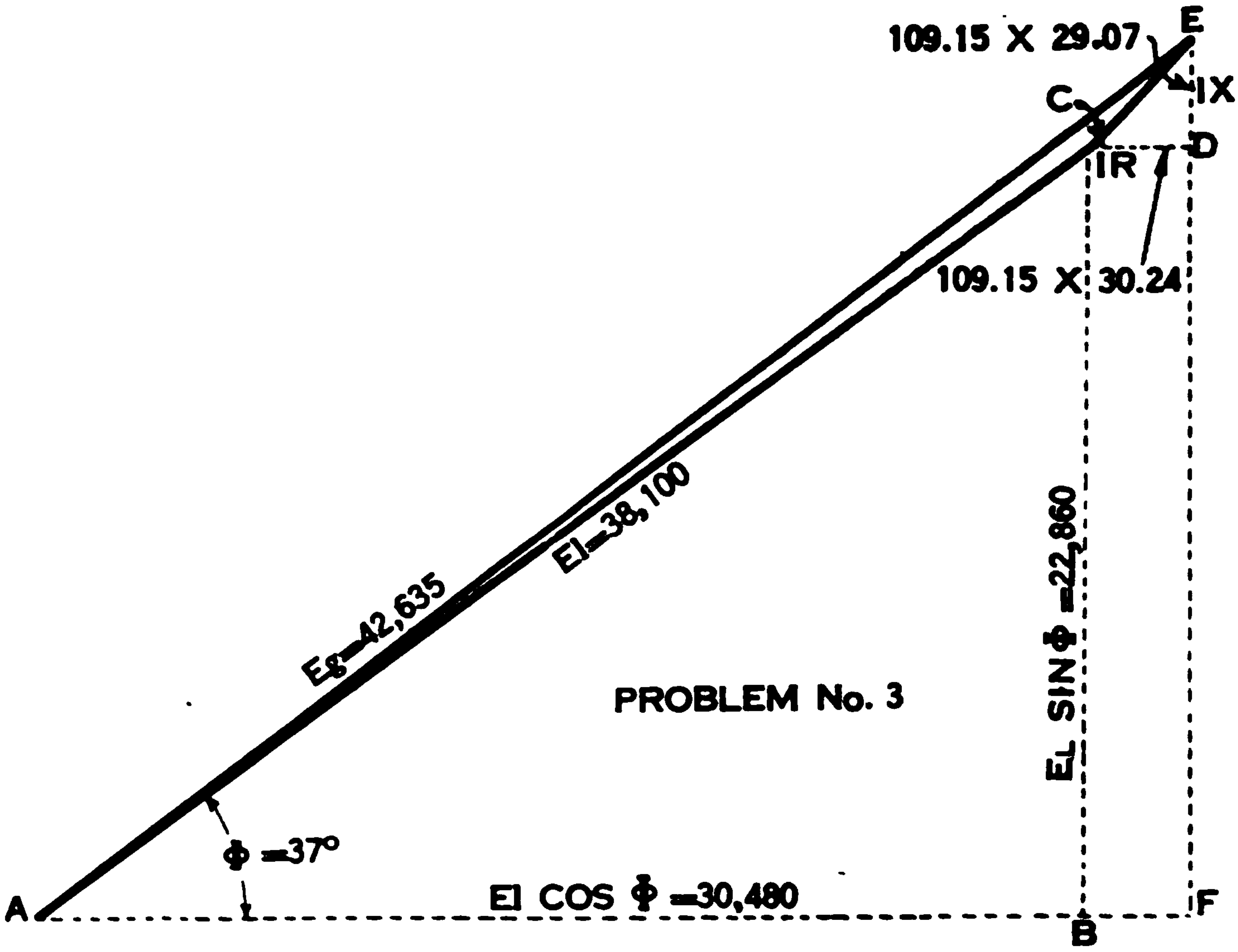


FIG. 1036.

total loss in the line C-E will be comparatively small, which means that the per cent regulation will be good.

Using the fundamental formula for this case, the regulation is:

$$Eg = \sqrt{(38{,}100 \times 0.80) + (109.15 \times 30.24)^2 + (38{,}100 \times 0.60) + (109.15 \times 29.07)^2}$$

Eg = 42,635 volts to the neutral at the station bus.

42,635 volts to the neutral times $\sqrt{3}$ equals 73,800 volts between line conductors.

$$\frac{Eg - El}{El} \times 100 = \frac{73{,}800 - 66{,}000}{66{,}000} \times 100 = 11.86\% \text{ regulation.}$$

The capacity effect in the circuit will now be considered. From the Standard Handbook or other reference work the charging current may be found for various size wires with different spacings and different frequencies. The charging current is based upon these factors and is given in fractions of an ampere per

FIG. 1037.—"π" line.

mile per hundred thousand volts to the neutral of a three-phase connection. For a No. 000 wire spaced 96 inches between centers on a 25-cycle circuit the charging current per mile per hundred thousand volts to neutral is 0.228 ampere. The total current will then be:

$$0.288 \times \frac{38{,}100}{100{,}000} = 0.08687 \text{ ampere per mile.}$$

$$0.08687 \times 90 = 7.818, \text{ charging current for the line.}$$

With reference to the capacity of the line the circuit may be considered as having half of the capacity concentrated at each

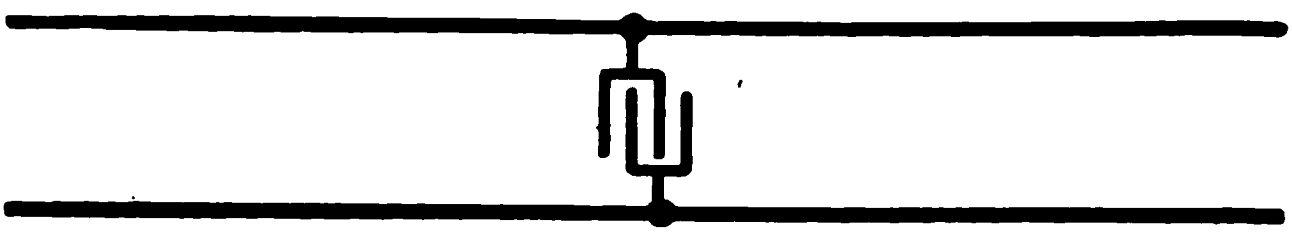


FIG. 1038.—"T" line.

end as in Fig. 1037. This is called a "π" line. Or it may be supposed that the entire capacity is concentrated halfway between the extremities as in Fig. 1038. This is called a "T" line. The actual charging current will be the same in either case. In this example it will be

$$\frac{7.818}{2} = 3.909 \text{ amperes.}$$

The correcting effect of this charging current upon the power factor and the reduction in total current circulating may be understood from an analysis of vector Fig. 1039. Here the line current for the load is *A-D*, differing from the energy component *A-B* by the angle Φ, which is the same as the angle between *A-E* and *A-F* in Fig. 1036. The reactive component of this current is *B-D*. The charging current for the line due to the capacity will be in direct opposition to the reactive component *B-D* or *D-C*. This will reduce the total current required by the

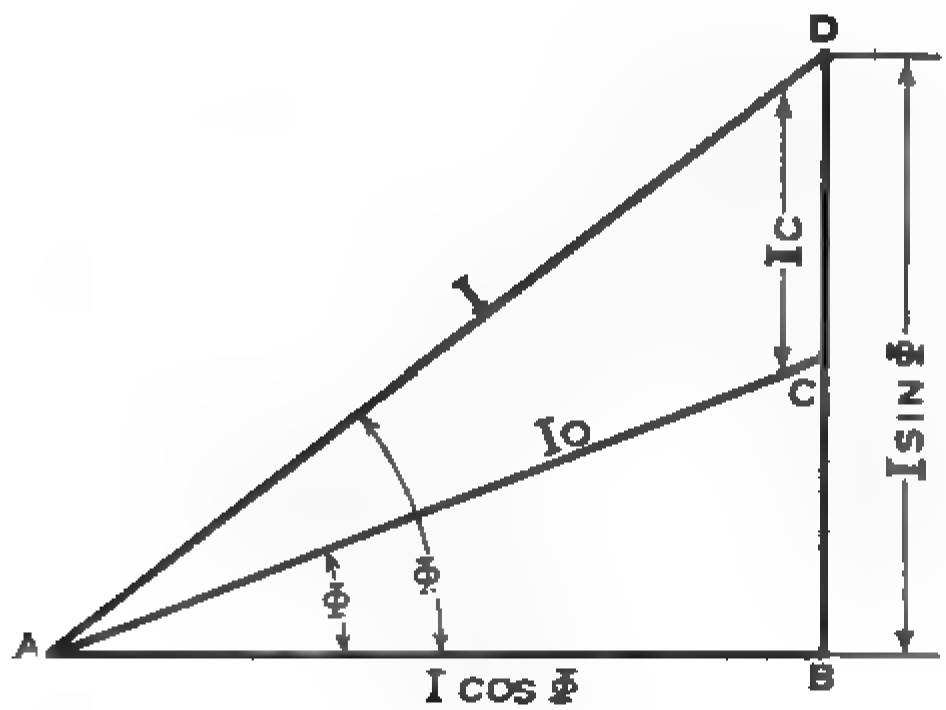


FIG. 1039.

circuit from *A-D* to *A-C*, and the angle of lag from Φ to Φ'. Hence the formula:

$$Io = \sqrt{(I \times \cos \Phi)^2 + (I \times \sin \Phi - Ic)^2}$$

Where:

Io = total line amperes.
I = line current without capacity.
Ic = charging current at the end of the line.
Cos Φ = power factor.
Φ = angle of lag.

Substituting:

$$Io = \sqrt{(110 \times 0.80)^2 + (I \times 0.60 - 3.909)^2}$$
$$Io = 108.2 \text{ amperes.}$$

It will be observed that the current, which was 109.15 amperes originally, is now reduced to 108.2 amperes. The voltage of the generator may therefore be reduced because a slightly smaller current is required. The actual voltage now called for will be:

$$Eg = \sqrt{(38{,}100 \times 0.80) + (108.2 \times 30.24)^2 + (38{,}100 \times 0.60) + (108.2 \times 29.07)^2}$$

Eg = 42,500 volts to neutral (approx.).

Line volts = 42,500 × $\sqrt{3}$ = 73,600 as against 73,800 previously required. The regulation will also be slightly improved as follows:

$$\frac{Eg - El}{El} \times 100 = \frac{73{,}600 - 66{,}000}{66{,}000} \times 100 = 11.50\%$$ regulation, as against 11.86% as before.

Thus it will be seen that the capacity of this transmission line slightly improves the conditions.

If it is desired to bring about a greater correction, the single transmission wires may be subdivided. It has been found that if a three-phase transmission line employing solid conductors arranged with a 10-foot spacing be reconstructed, each of the three wires being subdivided into three parts, these three smaller wires being spaced 18 inches apart, the effect would be to halve the inductance and double the capacity of the transmission circuit.

It must be understood that there are a number of other factors which enter into the determination of the actual regulation of a line. The preceding calculations simply outline the fundamental considerations involved.

SECTION XIX CHAPTER IV

TRANSMISSION OF POWER

ALTERNATING CURRENT TRANSMISSION

1. Required: The size of wire to deliver 3,000 k.w. a distance of 25 miles with a line loss of 10 per cent of the generated power. Power factor, 90 per cent; frequency, 60 cycles; nominal voltage of transmission, 60,000; spacing between wires, 72″.

2. Required: The size of wire to deliver 3,000 k.w. a distance of 7 miles; 6,300 volts at load; line loss, 8 per cent of the generated power; 60 cycles; power factor 93 per cent; spacing between wires, 24 inches.

3. Required: The size of wire to deliver 8,000 k.w. a distance of 100 miles; 70,000 volts at the load; 10 per cent of the generated power to be lost in the line; power factor, 85 per cent; frequency, 60 cycles. (Neglect the effect of capacity in the line.)

SECTION XX CHAPTER I

ELECTRIC RAILWAYS

ELECTRIC RAILWAYS; HISTORICAL; GENERAL PLAN

The first suggestion for an electric railway seems to have originated with Thomas Davenport, a Vermont blacksmith, who operated a toy motor on a small railway in 1834. In 1851, Moses G. Farmer operated an electric locomotive in which the source of power was stationary and current was conveyed to and from the car by means of the rails. In 1879 Siemens and Halske exhibited in Berlin a double-reduction motor and used a third rail for supplying current to the car through a sliding contact. In this experiment a generator was used for the first time as the source of power. In 1883 Stephen D. Field and Thomas A. Edison exhibited an electric locomotive at the

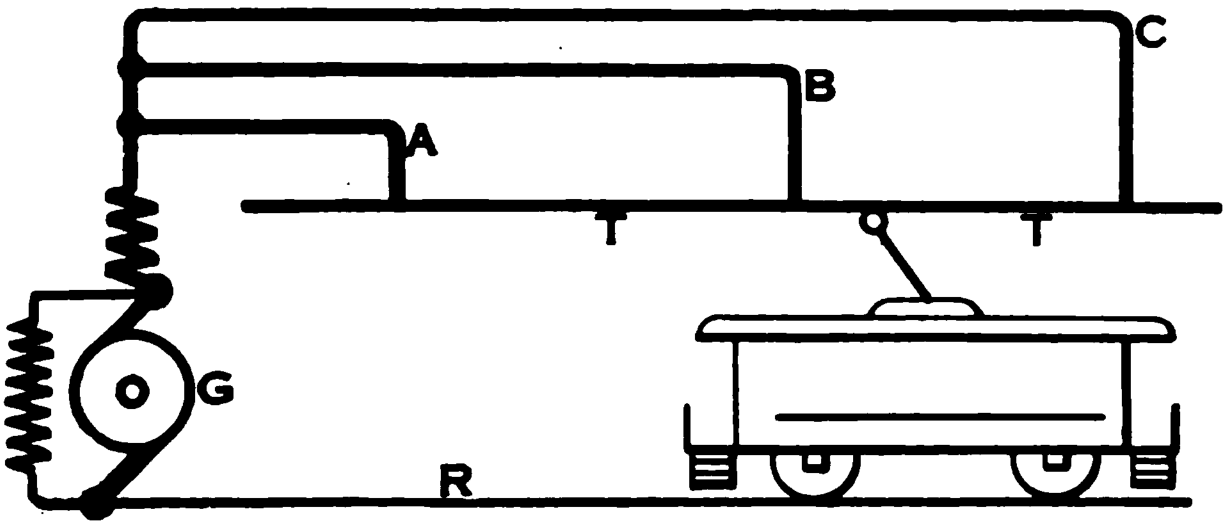


FIG. 1040.—Elementary circuits for overhead trolley line.

Chicago Railway Exposition. They had two Gramme machines, one of which was placed on the car as a motor and the other in a stationary position as a generator. The electro-motive-force was 75 volts. They found it necessary to reenforce the rails with a copper feeder to save power, as the resistance of the circuit at that low voltage consumed too large a percentage of the available pressure.

In 1886 Lieut. Frank J. Sprague began his experiments on the New York elevated lines and developed a successful propelling motor for that system. In 1888 Sprague opened the Richmond, Va., electric railway system, which was the first electric railway line operating on a large scale in the country. It included 13

miles of double track, 20 trolley cars, and a power station containing six 40-K W. generators.

The general scheme of the leectric railway is shown in Fig. 1040 A compound generator, G, or a rotary converter, supplies current at between 500 and 600 volts to a system of feeders, A-B-C, which

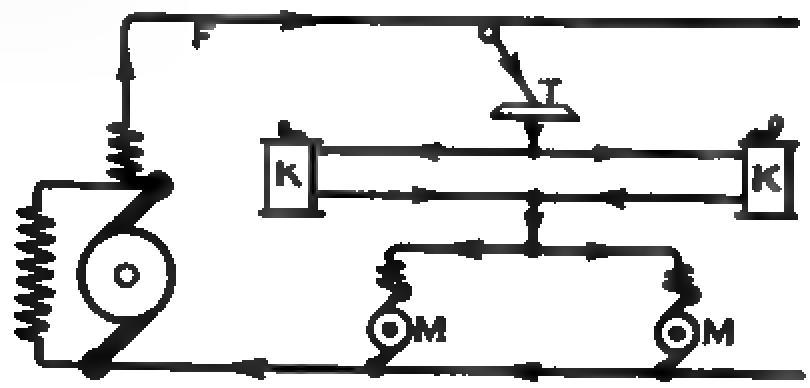


FIG. 1041 —Path of current through trolley, controller and motors.

convey the current to a trolley wire T. After passing through the car motors the current returns via the rails R to the generator. The motors are invariably series wound. Most of the later types have interpoles in addition to the main poles. Practically all street-car motors are four-pole machines. The current,

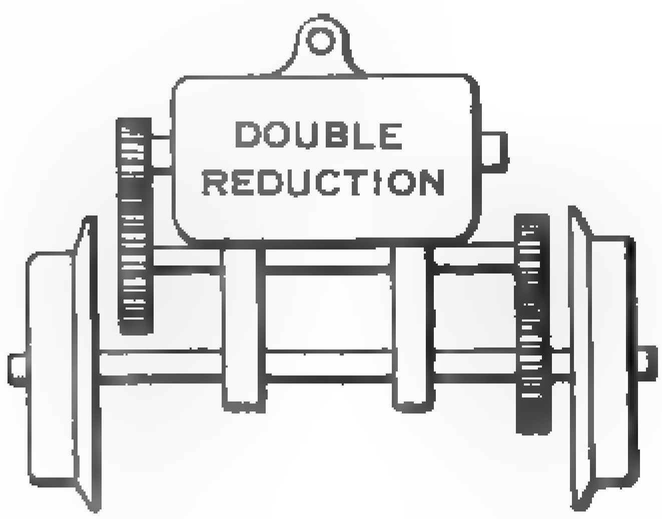


FIG. 1042. —Double-reduction gears between motor and car axle.

after passing through the trolley wire F, Fig. 1041, goes down through the trolley arm T, and then passes to one of two controllers K, whence it is led through the motors M-M and thence back by the rails to the generator. The motors are wound for the trolley voltage and are connected in parallel when operated at full speed. Provision is made in the controller for a low speed

by connecting the motors in series, thus dividing the trolley voltage between them without involving any rheostatic loss. The early motors were high-speed machines and employed a double-reduction gear between the shaft of the motor and the axle of the car as in Fig. 1042. Motors were subsequently designed for a lower speed so that the intermediate or counter shaft was eliminated, the pinion on the armature shaft engaging a gear placed directly on the car axle as in Fig 1043. This was followed by an entire elimination of gears in Fig 1044. Here the armature surrounds the axle of the car, which revolves with it. The field structure surrounds the armature and is attached to the running gear so that it may be held in position while the armature revolves. Obviously the size and weight of the motor must be increased in direct proportion to the reduction in speed; hence the gearless motors were very heavy and costly. As the design of the transmitting gear was improved and a housing provided to keep the noise in and the dirt out

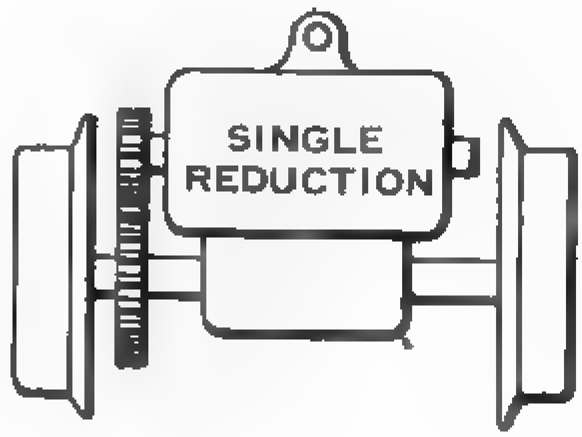


FIG. 1043.—Single-reduction gearing between motor and car axle.

FIG. 1044.—Gearless drive.

and permit of lubrication, the early objection to gear reduction was largely overcome, and the gearless motor for street cars was abandoned and the single-reduction motor of Fig. 1043 was adopted as the standard form for street-car equipment. This is almost universally used today.

Methods of Feeding.—The system of feeding the trolley most commonly employed is illustrated in Fig. 1045. It is called the

ladder system. From the generator, *G*, current is led out over the feeder *F*, which parallels the trolley *T* throughout its length. At intervals of 600 feet, more or less, depending on the amount of load and the size of equipment, taps are taken at the points *B-B-B*, to connect the feeder to the trolley wire. The feeder is usually a stranded cable of 250,000 or 500,000 circular mils. The trolley wire is usually a No. 00 or No. 000 hard drawn copper or silicon bronze wire of sufficient tensile strength to permit of being drawn very taut.

In some cases the trolley wire is sectionalized and supplied with independent feeders and each section directly connected to the power house. While this is more costly than the ladder

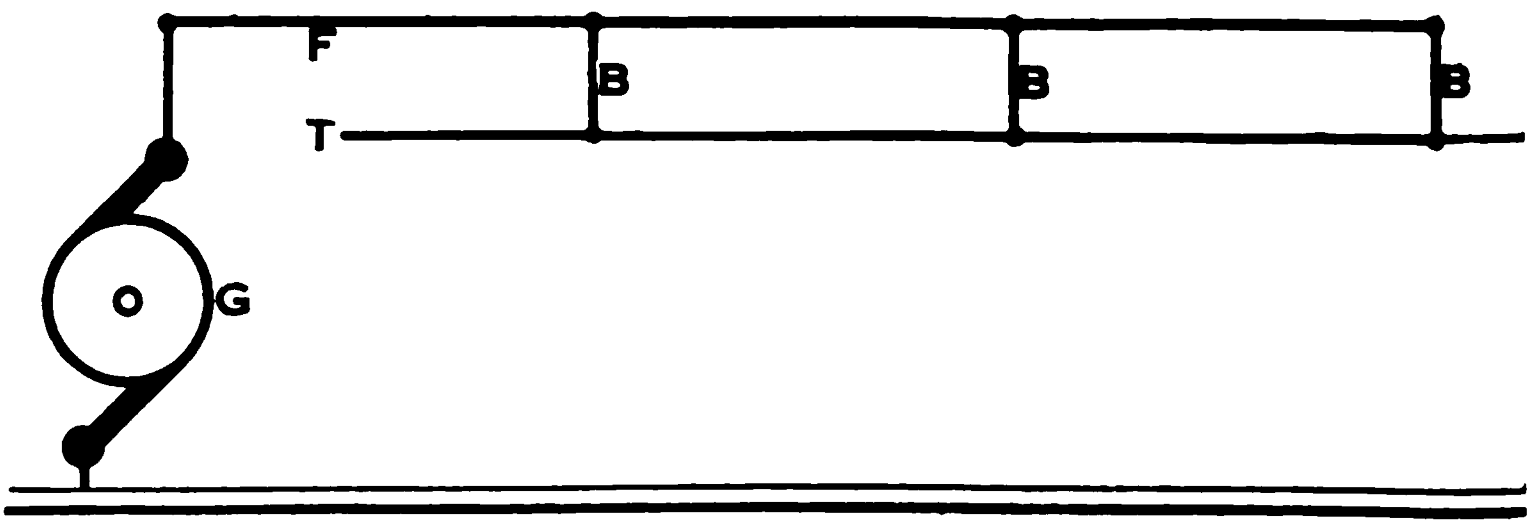


FIG. 1045.—Ladder-system of feeder and trolley wires.

system, it permits of disconnecting certain sections of the trolley in the event of trouble.

Electrolysis.—If a steel rail of 7 to 10 times the cross-section of the trolley wire is employed for the return circuit, its resistance will be equal thereto. The resistance of the joints on the rails, however, causes a considerable drop in potential. As the rails lie on the ground, opportunity is afforded for the returning current to leave the rail and flow back to the power station over any parallel conducting circuit. In most cities the water, sewer and gas mains parallel the tracks and are often in close proximity thereto. The result is, that the current after passing from the generating plant out over the trolley, as in Fig. 1046, and then through the car, upon attempting to return, finds it comparatively easy to leave the rail at the point *C* and pass through the moist conducting earth to the pipe line *A*, thence returning toward the station. When it reaches the location *B* it must leave the pipe line and reenter the rail in order to reach

its objective point, which is the negative side of the generator in which it originated. At the point *A* the pipe line is negative and no effect is produced. At the point *B*, however, electrolytic action is set up because *B* acts as the anode, *D* as the cathode, and the moist earth between as the electrolyte of an electrolytic cell. The oxygen evolved at *B* combines with the lead or iron pipe to dissolve it. If this action is allowed to proceed, the pipe will

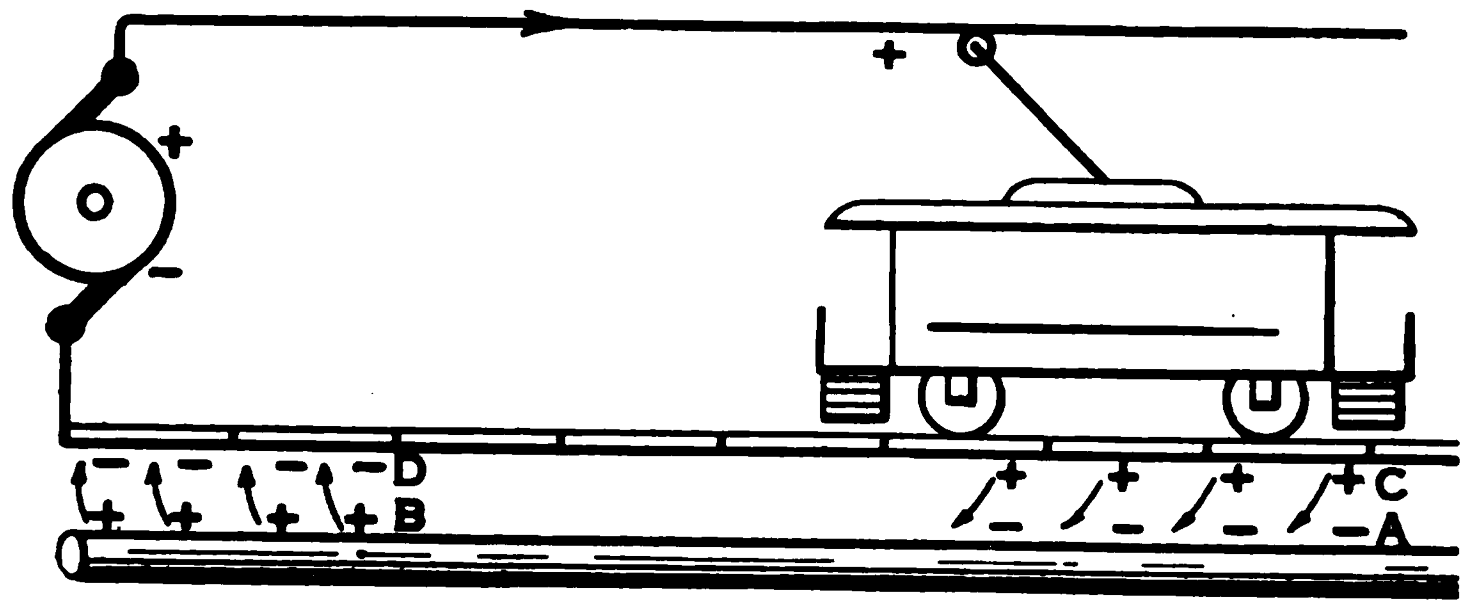


FIG. 1046.—Electrolysis in pipe lines, parallel to rail return of electric railway circuits.

eventually be dissolved. One ampere of current will dissolve in this way 70 pounds of lead pipe or 20 pounds of iron pipe in a year. As modern railways involve currents running up to thousands of amperes, some idea of the destructive results on the pipes of a city may be imagined if this action were allowed to continue. To prevent this, municipal regulations require that all joints of the rails carrying current for street cars must

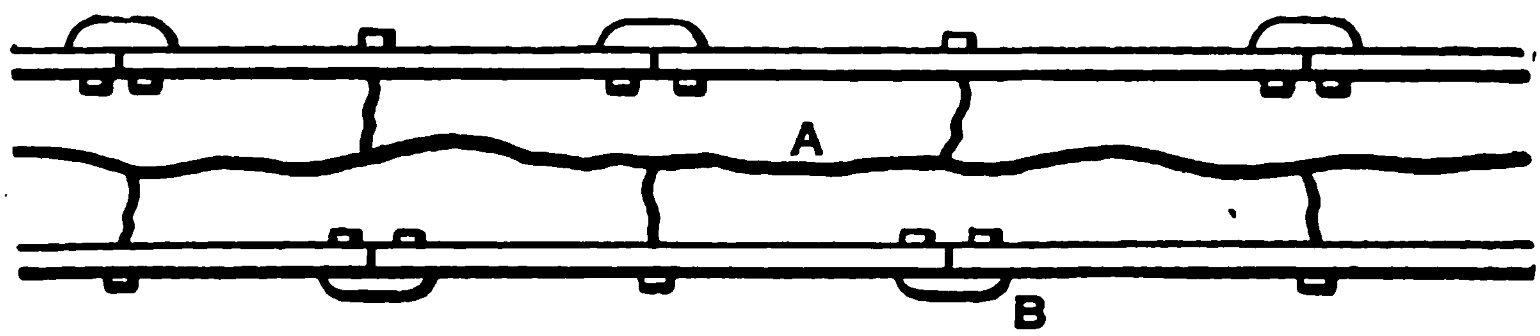


FIG. 1047.—Return feeder and rail bonding to avoid leakage currents.

be thoroughly **bonded.** This consists in bridging the gap at the rail joint by a copper bond which is either riveted or preferably welded to the ends of the rails at *B*, Fig. 1047. In some cases the rails themselves are welded together. In addition to this it is sometimes desirable to run in the ground a negative feeder of bare copper which is tapped into the various sections of the

rails, tying them all together in one conducting network of low resistance as shown at *A*, Fig. 1047. In this way the tendency for current to stray into parallel pipes is largely avoided. If the rails were connected by wires with the pipes, the electrolytic action would still further be reduced. In some localities the rails are not permitted to be used as a return circuit at all, but two trolley wires and two trolley poles are required, the current flowing out over one and returning through the other. Both wires are insulated from each other and from the ground by composition insulators of considerable mechanical strength.

Track Switch.—A form of track switch controlled from the car by the motorman is shown in Fig. 1048. The point of this switch is attached to an arm which may be moved into either of its two extreme positions by means of two solenoids, *E* and *F*. These solenoids are controlled by the motorman, who places the

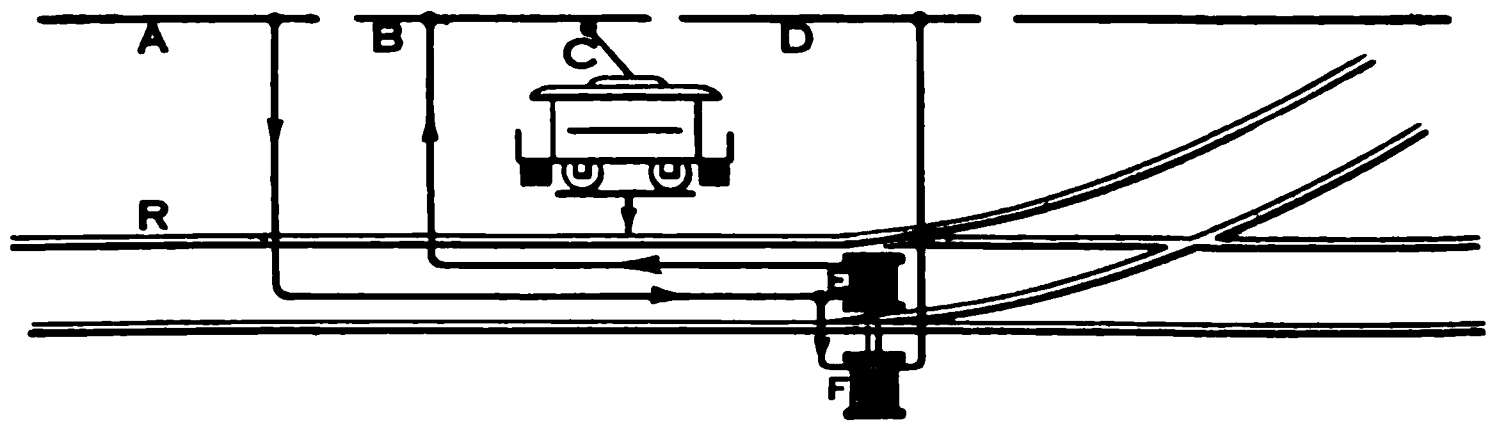


Fig. 1048.—Electro-magnetic track switch controlled from car.

controller in the "on" position when the car is on a certain section of the trolley wire to operate the switch in one direction and places it in the "on" position on another section of the trolley wire when the switch is to be thrown into the reverse position. With the controller on, and the car in the position shown, current from the trolley will pass from *A*, through the solenoid *E*, thence back to the section *B* and down over *C* and through the car and thence back through the rails. The motor current is sufficient to operate the solenoid and throw the switch, thus allowing the car to proceed straight ahead. If it is desired to turn off the main track, the motorman leaves his controller "off" and coasts over the section of trolley *B*, throwing his controller on when the trolley pole reaches the section *D*. Current will then flow from the section *A* through the solenoid *F* and the trolley section *D*, thence through the car and back by the rail, moving the switch so as to divert the car from the main track. In some types

the switch is held in the normal straight-ahead position by means of a spring. From this position it is thrown by means of a solenoid against the tension of the spring and is held in this position by means of the controller, current being kept on all the time the car is passing the switch.

Block Signals.—A simple form of block signal for electric railways is shown in Fig. 1049. Here a car, entering the single-track section at the point A, must control the block extending to B so that cars will not enter at either end until the first car leaves the block. Upon entering this section of the track the motorman therefore throws the switch S into the position shown, and current from the trolley wire T passes through the switch at B, the lamps M, thence through the pilot wire R, and the lamps L, and the switch at A, and back to the station through the rails Y. All other cars are thus warned not to enter the block from

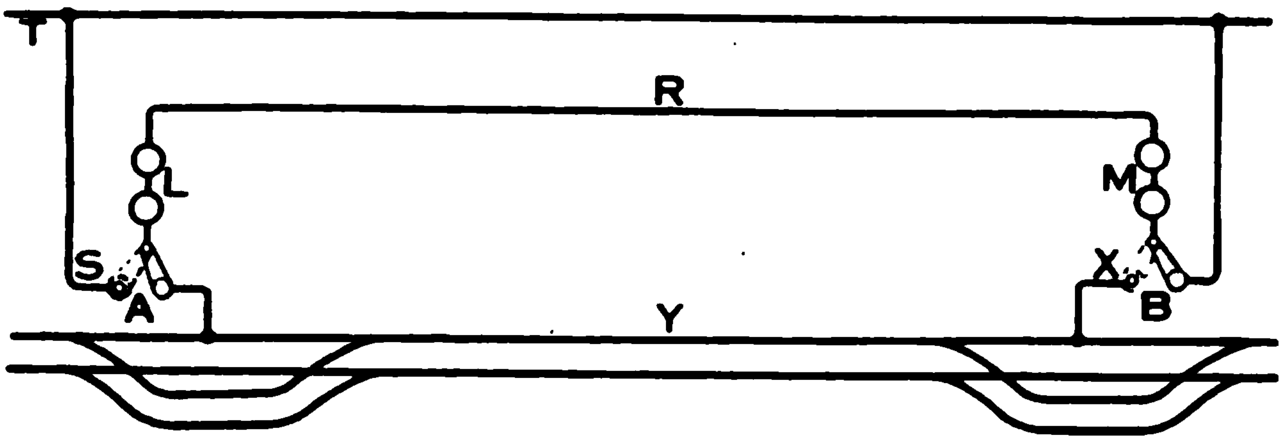


FIG. 1049.—Simple block-signal system for single-track electric railway lines.

either end. When reaching the point B, the switch X is thrown into the dotted position, which extinguishes the lamps. Cars may now enter the block from either end, the motorman controlling the block by throwing either switch into the alternate position. The switches are of the three-point variety, by means of which the lamps at both ends of the block may be turned on or off from either end regardless of the position of the switch at the other end.

Car Wiring.—Fig. 1050 shows the arrangement of the wiring for a car equipped with an overhead trolley. Current passes down the trolley pole and enters the car at the point A. From this it passes through a circuit breaker placed over the motorman's head at B and in series with a similar one at the other end of the car over the conductor's position at C, thence through a fuse box under the car at F, and through a lightning arrester at H, which has a branch with a ground wire for the purpose of

conducting any current caused by lightning discharge to earth via the ground wire *G*. Passing on from the lightning arrester, the current for the motors is next led through a choke coil

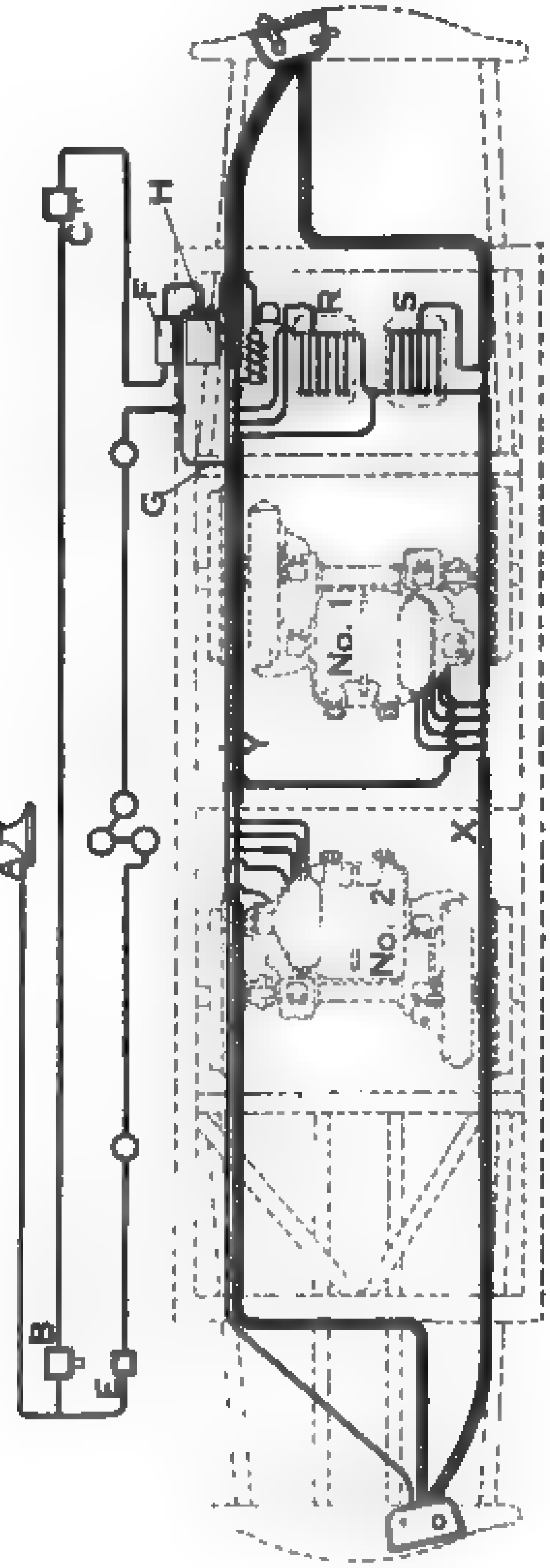


FIG. 1050.—General layout of electric equipment on a two-motor single-truck car.

D, consisting of several turns of heavy wire around a wooden core 2 inches in diameter. While this does not offer an appreciable opposition to the passage of the direct current for operating

the motors, it affords an effective barrier to the passage of any lightning discharges which are of high frequency. The discharge is therefore backed out and compelled to take the alternate path through the lightning arrester to the ground. The direct current, after passing through the choke coil, enters the

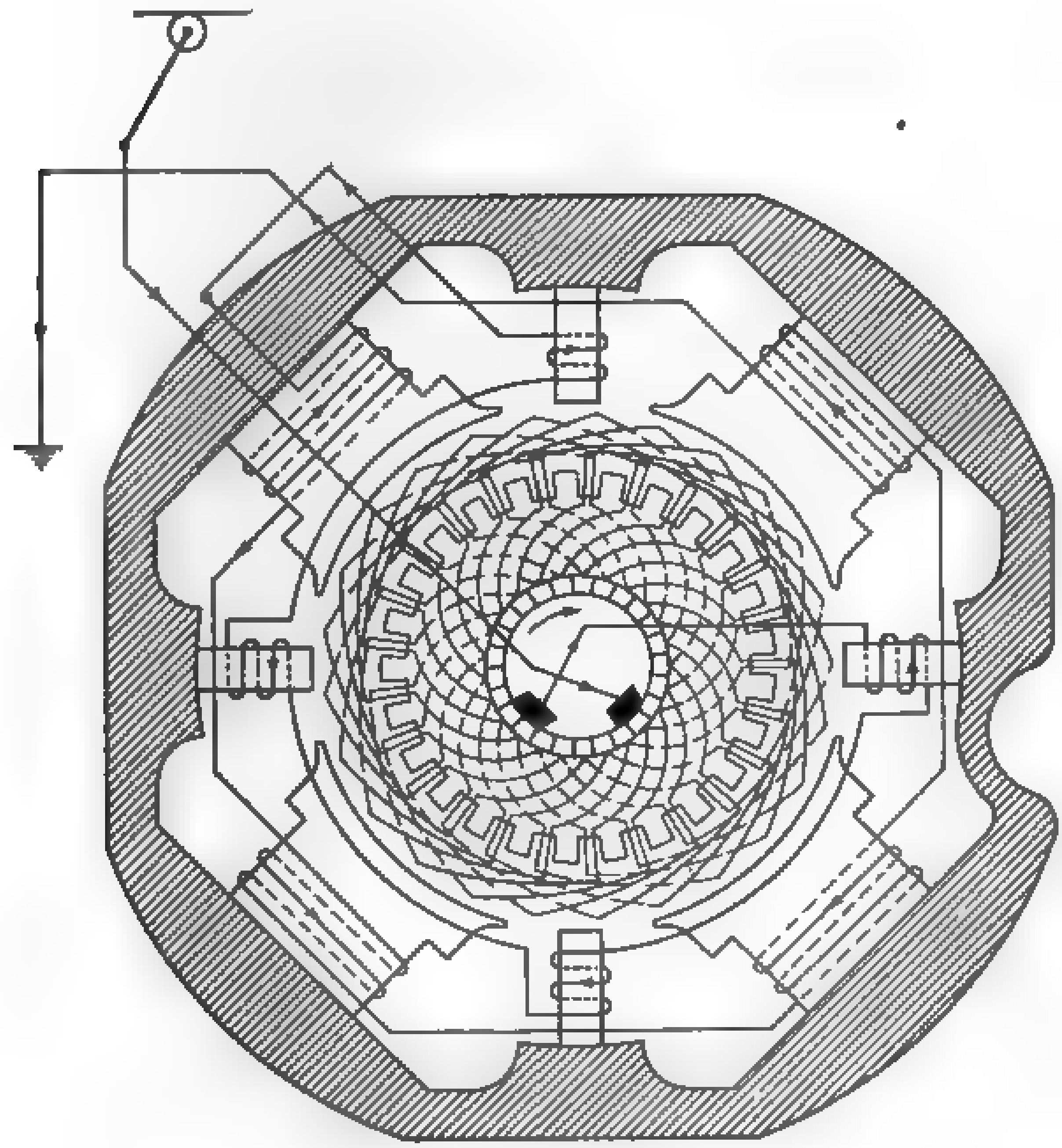


FIG. 1051.—Electrical circuits in Westinghouse railway motor, showing series-wound armature, main series field and commutating pole field.

cable *Y*. There are two of these cables extending the length of the car between the controllers. Cable *Y* supplies motor No. 2, and cable *X* supplies motor No. 1. Both of these cables terminate at the controllers so that both motors may be independently operated or disconnected from either end. Resistance

grids, R and S, are employed in series with the motors when starting, to lower the initial current to a safe value. Current is taken from behind the circuit breaker B and led through a combined switch and cut-out, E, which supplies the lighting circuit. This circuit consists of five lamps in series with any number of sets in parallel according to the size of the car. There are usually 10, 15 or 20 lamps in a car. The object in connecting this circuit behind the motor circuit is in order that the car may have light in case it becomes necessary to disconnect the motor circuit for examination or repair of the motors while on the road at night.

Motor Equipment.—Street cars employ series motors for two reasons:

First, because they have the **variable field feature** which automatically changes under variations in load, thus giving the motor the great torque needed at the start.

Second, and as a result of the first, these motors have a widely varying speed. The motors are thus enabled to raise the speed

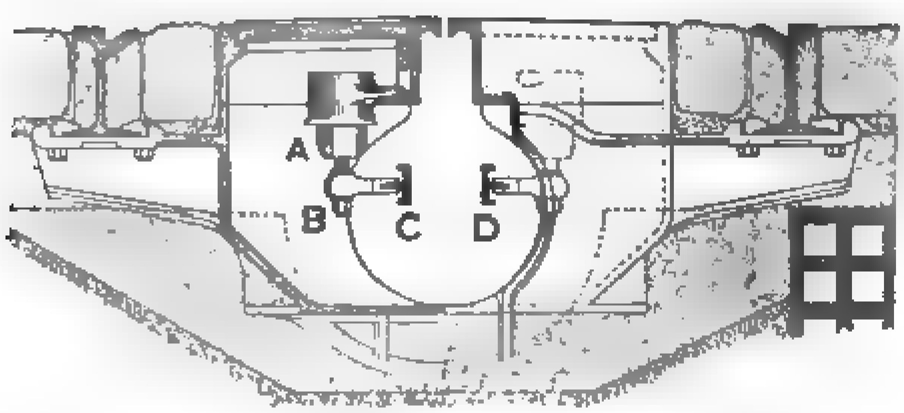


FIG. 1052.—Conduit railway system showing conductor bars for metallic insulated circuit and supporting insulators.

of the car when the load is light, while a heavy load brings about a reduction in speed, which is accompanied by an increasing torque until a balance is obtained for any particular load.

Fig. 1051 gives a sectional view of an interpole series motor for railway purposes. The commutating poles, main poles and armature are all connected in series.

Conduit System.—Because of the unsightly appearance of overhead trolley wires and the congested conditions in large cities, the open-conduit system shown in Fig. 1052 has been quite generally adopted. Massive iron yokes weighing from

200 to 400 pounds are placed on edge at intervals of from 3 to 5 feet along the roadway. The rails which carry the car are bolted to these yokes. The whole is set in cement with a large conduit, opening through a narrow slot about $\frac{3}{4}$ of an inch wide in the center between the tracks. Massive insulators *A*, mounted in cast-iron bell-shaped supports, are used to carry a bolt *B*, to which are attached the conductor bars *C* and *D*. These conductor bars are of steel, with a *T* cross-section, 2 inches wide horizontally and 4 inches high vertically. This gives a very rigid construction mechanically. These conductor bars weigh approximately 23 pounds to the yard and have a conductivity corresponding to about 300,000 c.m. of copper. They are placed about 6 inches apart, far enough back in the conduit to

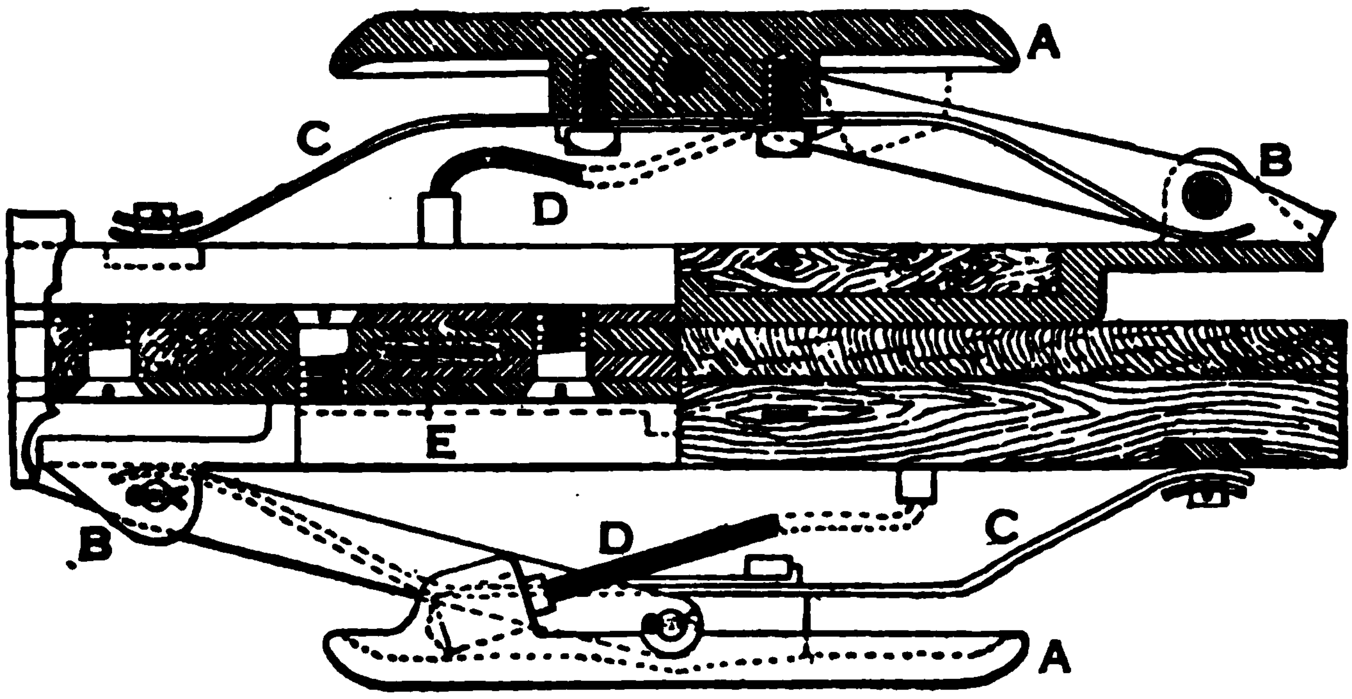


FIG. 1053.—Plow and shoes for conduit railway system.

prevent water from dripping through the slot onto them. Traveling between these conductor bars is a plow shown in section in Fig. 1053. This consists of two cast-iron shoes, *A-A*, which are hinged at the point *B* and held under tension by means of springs, *C*. Current leads from each shoe, through a braided flexible copper conductor *D*, into the frame of the plow. This conductor is bare and of such cross-section that it forms a fuse of last resort, so that in case the circuit breaker on the car sticks or the main fuse fails to blow, this copper fuse in the bottom of the plow will give way before the motor burns out. The current continues through the frame to the conductor *E*, surrounded by a taped insulation, up through a slender steel portion of the plow, designed to pass through the slot and hung from the running gear of the car. The terminals are attached

by plug connections to the car circuits and arranged so that they may be readily separated when it is desired to change the operation of the car from underground to overhead connections, as is customary when cars pass from the crowded city sections to suburban lines. The conductor bars form the positive and negative terminals of the electrical source and are divided into sections, approximately one-half mile or one mile in length and supplied with current through independent feeders.

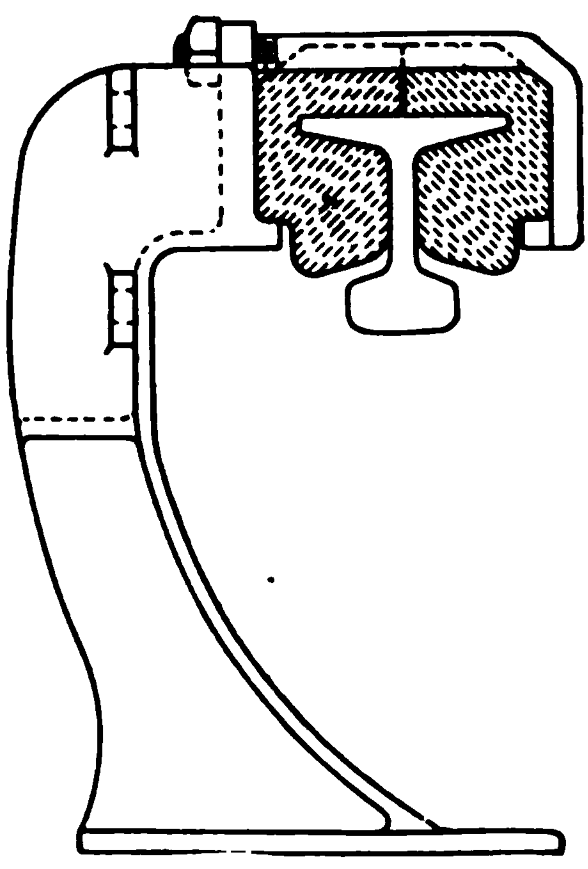


FIG. 1054.—Insulator and support for inverted third-rail for supplying current to cars on the third-rail system.

Third Rail.—In addition to the preceding methods of collecting current for the car or locomotive, the "third rail" construction may be employed. This consists of a steel rail mounted about 6 inches above and 12 inches to one side of the track rails. An over-running or under-running shoe, depending upon whether the rail is mounted right side up or inverted, is attached to the trucks of the car and is employed to collect the current. These shoes are placed on both sides of the trucks at both ends of the car, so that the third rail may be located on either side as may be most convenient. Fig. 1054 illustrates one form of supporting arm and insulator for this type of construction.

Resistance of Steel Rails.—The resistance of the carrying rails, the third rail or the conductor bars of any railway system may be computed approximately from the following simple formula:

$$R = \frac{0.848}{w}.$$

Where:

R = resistance in ohms per thousand feet.

w = the weight in pounds per yard of steel rails.

SECTION XX CHAPTER I

ELECTRIC RAILWAYS

ELECTRICAL RAILWAYS; HISTORICAL; GENERAL PLAN

1. What type of motor is invariably used for electric car propulsion?

2. Explain the general scheme of an overhead trolley system including generator, trolley wires, track, motors and method of control.

3. What are the relative advantages of single reduction and gearless motors.

4. Explain the plan, object and advantages of the "ladder" system of feeding a trolley wire.

5. (*a*) Explain how "electrolysis" in pipe lines parallel to the rail-return of trolley systems comes about.

(*b*) How may it be prevented?

6. Explain the action of the electromagnetic track switch which is controlled by the motorman from car. Sketch.

7. Sketch and explain a simple block signal system for single track railway lines.

8. What are the peculiar advantages of series motors for railway work?

9. Explain the method of supplying power to the car in a conduit railway system. Sketch.

10. What is the general plan of the third-rail system? What are its advantages?

11. What is the resistance per mile of a steel third-rail weighing 70 pounds per yard?

ELECTRIC RAILWAYS

CONTROLLERS

Practically all street car controllers employ the series-parallel principle designed by Sprague, and can be employed only with equipments consisting of two or four motors. When starting, two identical motors are placed in series with each other and in series with a resistor across the source of supply. This gives each motor a very low voltage. Sections of the resistor are gradually short-circuited and the motors brought up to the full series position without any resistance in circuit. They are then placed in parallel, and the resistor is again inserted in series. On this step a sufficient amount of resistance must be included in the circuit to prevent too great a jump in speed from the last series connection to the first multiple connection. Sections of the resistor are again cut out until the motors come up to the full multiple position, where they operate at line potential.

This control for motor operation is, in a way, similar to the three-wire system for lighting. There, it will be remembered, the current is transmitted at 220 volts and utilized at 110 volts without rheostatic loss. That is, the three-wire system affords two fundamental potentials, one just one-half the other. The same system can be used for the operation of a single motor giving two fundamental speeds. The series-parallel control reverses this condition and uses one fundamental potential divided between two motors. This again gives two fundamental speeds, one at 250 volts, when the two motors are connected in series, and the other at 500 volts, when they are in parallel. The rheostatic losses in acceleration are thus very greatly reduced below what they would be, if a single motor were operated with rheostatic control only.

Types of Controllers.—The General Electric Company has developed a number of different kinds of controllers based upon the general scheme devised by Sprague.

"K" controllers: These are series-parallel controllers which include the shunting or short-circuiting of one motor when changing from series to parallel combinations.

"L" controllers: This type is a series-parallel controller which completely opens the power circuit when changing from series to multiple connections. It was designed especially for large motor equipments. It has now been superseded by the **Type "M"** control.

"R" controllers: These are designed for mine hoists and mine locomotives and involve rheostatic control only for one or more motors.

"B" controllers: These may be either rheostatic or series-parallel but are generally the latter. The distinguishing feature is that they include connections for the operation of electric brakes.

"M" controllers: This involves series-parallel operation, in which the motors are controlled through the medium of a master controller which operates a number of electro-magnetic switches or contactors which are simultaneously controlled in a number of cars on the multiple-unit system.

"C" controllers: These are small master controllers designed for operating the magnetic switches in the **"M" system** of control.

Series-Parallel Control.—One of the oldest forms of controller was the *K-2*. This employed the principle of shunting the motor fields on the last series and last multiple notches. It could be used also without these shunts. It had nine fixed notches on the top of the controller, five series and four multiple. It was designed to handle two 40-horse-power motors. The circuits were established in the manner shown in Fig. 1055. On the first notch a section of starting resistance, R, and two motors are in series across the line. On the second notch a section of this resistance is short-circuited. On the third notch another section is short-circuited. On the fourth notch the entire resistance is short-circuited, and the line potential is equally divided between the two motors. On the fifth notch a shunt resistance, S, is placed across the motor field windings. This weakens the fields and yet reduces the total resistance across the line so as to increase the armature currents. The motors are thus accelerated. Between the fifth and sixth notches a wide gap is provided in the controller so that short-circuiting may not occur while changing from series to parallel connections. The first intermediate notch reintroduces a section of resistance so as to lower the current in the motors. Next, motor No. 2 is short-

circuited, the starting resistance checking the rise in current Finally, motor No 2 is removed from under this short circuit. As the controller cylinder reaches the sixth notch, motor No. 2 is swung into parallel with motor No. 1, and the current of motor No. 1 is divided between the two. On the seventh notch another portion of the starting resistance is short-circuited. On the

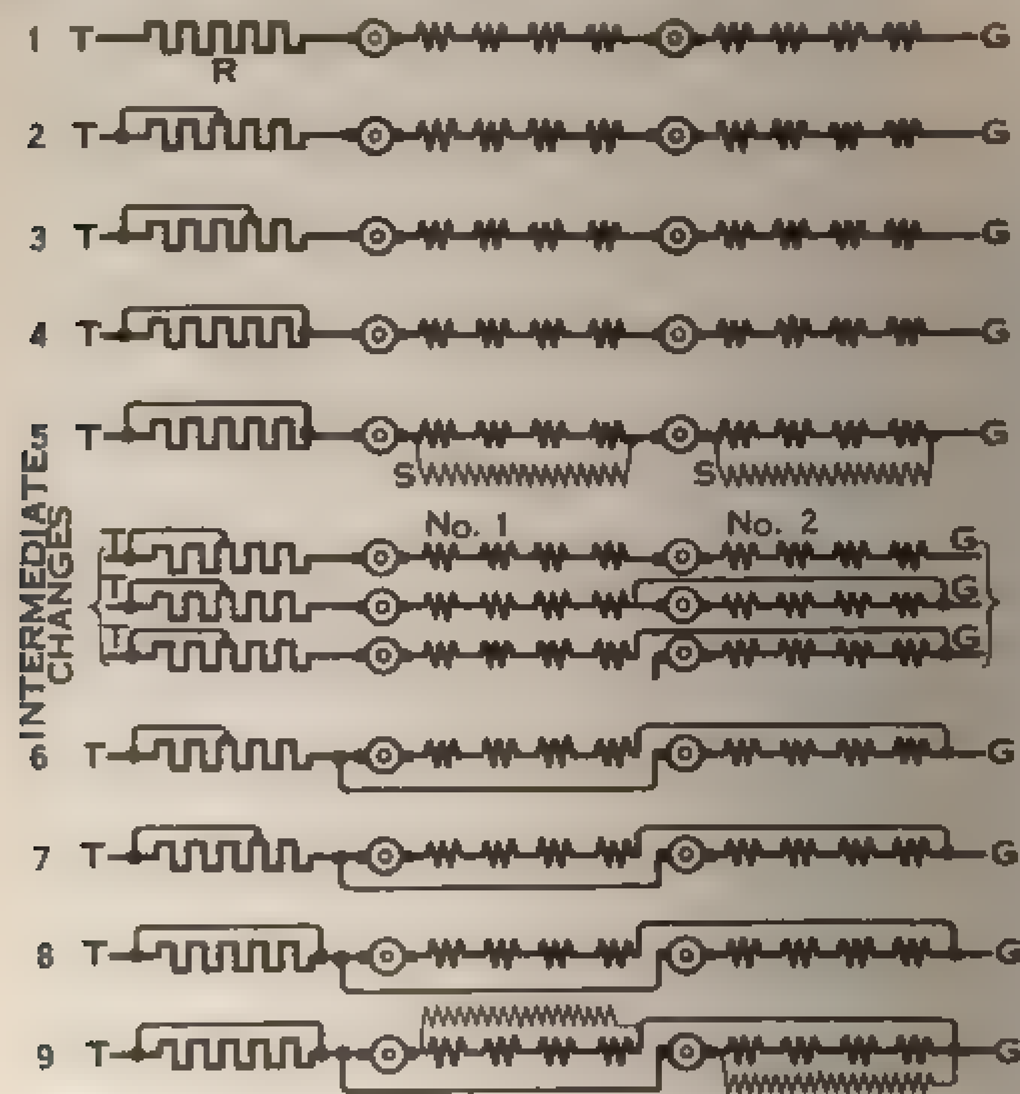
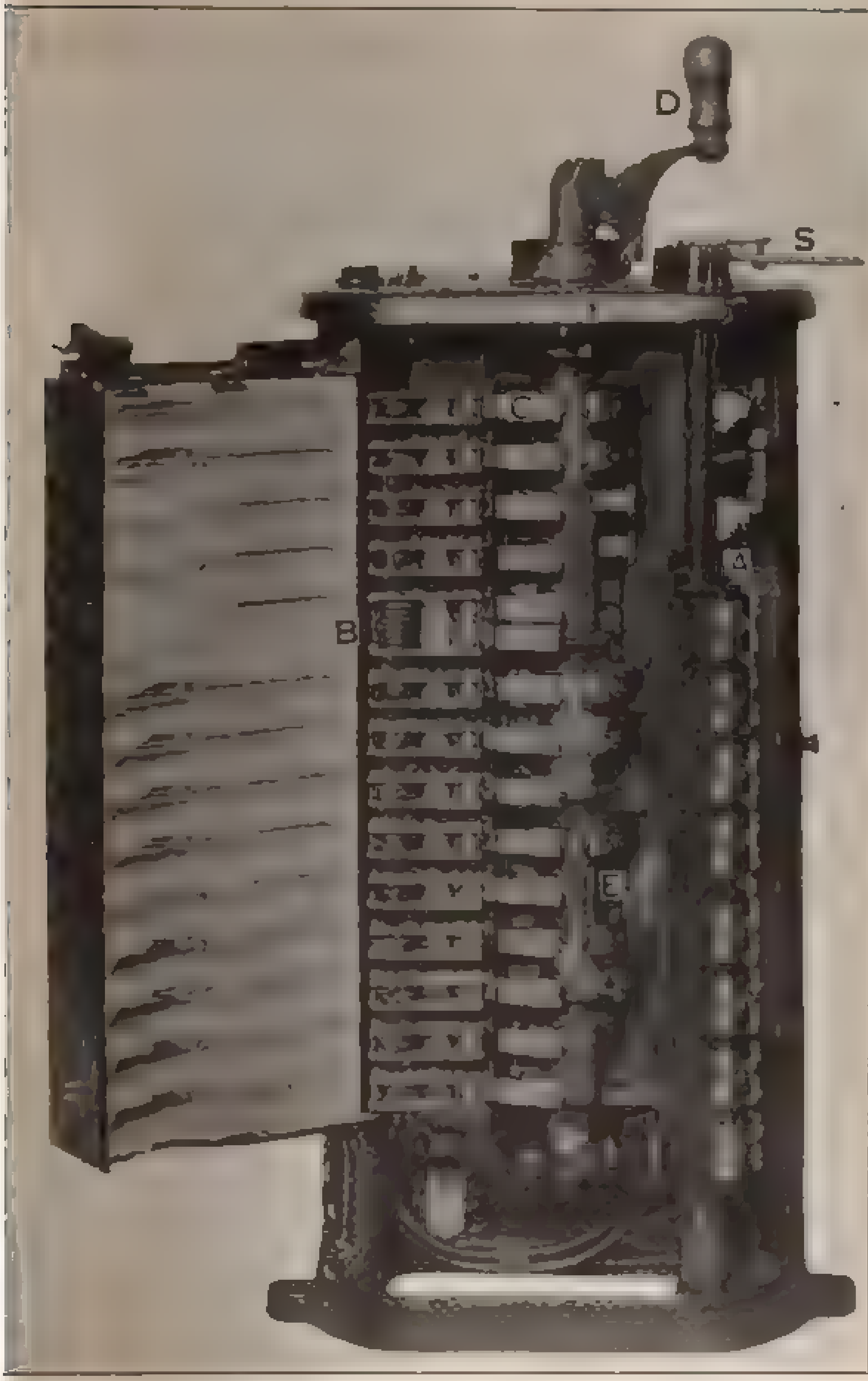


FIG. 1055 Various combinations of motors and resistors effected by the type K-2 General Electric series-parallel controller

eighth notch it is all short-circuited, and on the ninth notch the fields are again shunted.

The *K-9* controller superseded the old *K-2* It did not use the field shunts and thereby eliminated two contact fingers on the power cyclinder required for operating the shunt resistances. It had, however, one finger for an additional series resistance, there being four sections of the starting resistance in this type It was adapted for two 40-horse-power motors and employed



IG. 1056.—Modern, type K 35, form GR 2, series-parallel controller built by the General Electric Company.

only two running positions, namely, the full series and full shunt, while the *K-2* controller with the shunts gave four running positions. This type has also been superseded by a later design, the *K-35* illustrated in Fig. 1056, which accomplishes practically the same results. There are two cylinders operated by handles from the top, *A*, the reverse drum, operated by the handle *S*, and *E*, the power drum, operated by the handle *D*. These drums are mechanically interlocking As *A* is a reversing switch it would not do to reverse the current in the motor when the starting resistance was cut out, therefore the two drums are mechanically interlocked so that, if the handle *D* is "on," the handle *S* is locked so that it cannot be moved. Likewise, if switch *S* is in the "off" position, *D* is mechanically locked so that it cannot be moved. Two motor circuit switches are provided for cutting out either motor in case of trouble. These switches control the motors from this particular controller only. If a motor is to be cut out when the car is operated from the other platform, the motor circuit switch on that controller must also be opened.

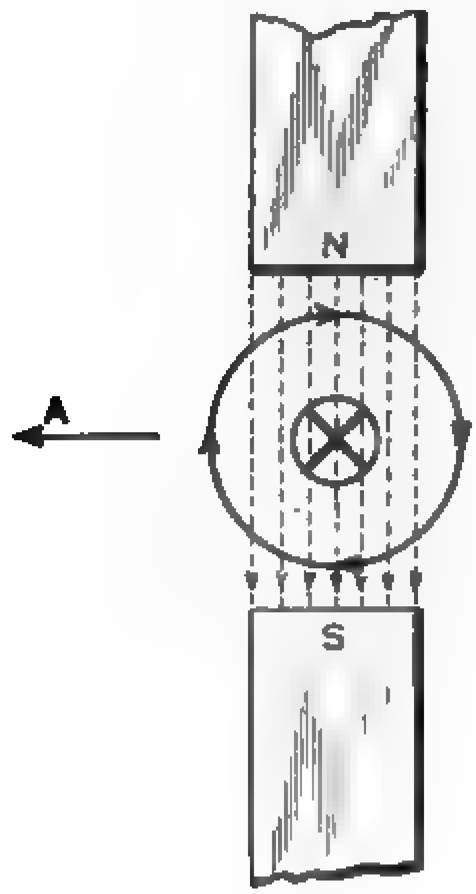


Fig. 1057.—Principle of magnetic blowout.

In interrupting the current on 500-volt circuits the arc established would cause short circuiting between contacts across which a high potential existed, unless special precautions were taken. This is accomplished by means of powerful blow-out magnets. It is a well-known fact that an arc cannot be maintained in the presence of a powerful magnetic field. This is because the arc is a flexible conductor If a current passed through an arc vapor away from the observer at the point *X*, Fig 1057, a magnetic flux about this path would be created, as shown by the circle If this arc were projected through the path of a powerful magnetic field in the direction *N-S*, the arc would tend to move in the direction *A* As the arc consists of a very frail path, it is forced violently in this direction and

almost instantly ruptured. Under favorable conditions an arc on a 500-volt circuit may be maintained over a gap of 6 or 7 inches. With a powerful magnetic field across the path, such an arc would be quickly ruptured across a gap $\frac{3}{4}$ of an inch in length. The magnetic blow-out is essential to the success of a railway controller where the fingers connecting to opposite sides of the circuit are in such close proximity to each other. Therefore the current entering the controller passes through the coils of powerful electro-magnets, *B*, Fig. 1056, on its way to the motors. The resulting flux effectually ruptures all arcs produced across the contact fingers.

The **Type "M"** system of control is a series-parallel arrangement through the medium of a master controller, which operates

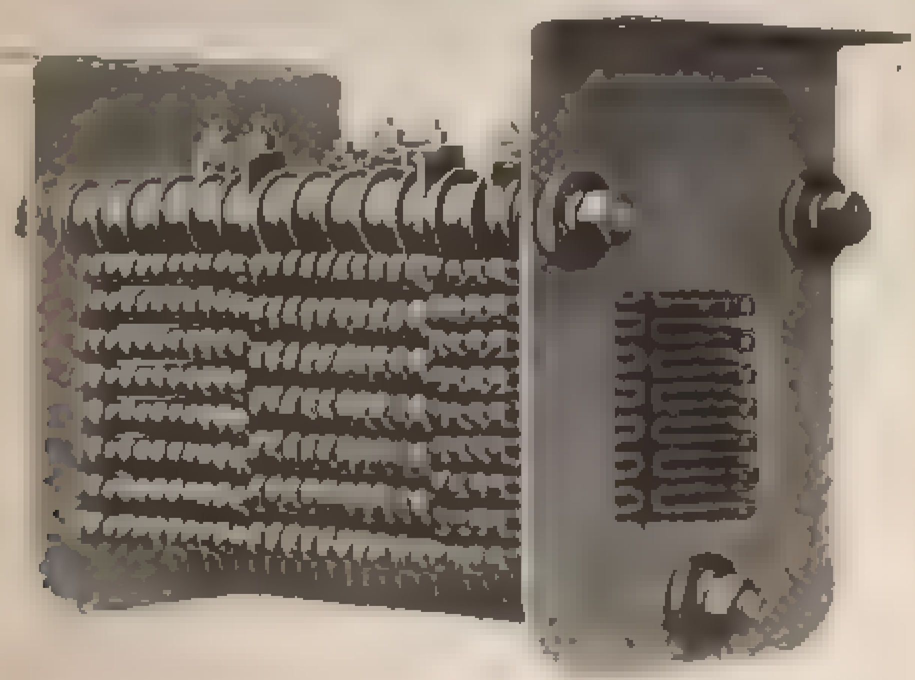


FIG. 1058. Cast iron No. 14 resistor, built by the Westinghouse Company for railway controllers.

a number of electro-magnetic switches or contactors. The master controllers for manipulating these switches are designated by the letter *C*. One of these was the *C-6*. It involved a safety switch consisting of a button which was operated by depressing a knob on the top of the handle, so arranged that, if pressure upon this knob failed, as might occur if a man were disabled at his post, power would be automatically shut off and the train would come to a stop. It had five series and five multiple notches. The handle was connected to the power cylinder by a spiral spring. The rotation of the power cylinder was limited

by an electro-magnetic lock so that, no matter how fast the handle was moved, the power cylinder would notch up automatically at a rate which prevented the acceleration exceeding a certain amount, this amount being determined by the adjustment of the electro-magnetic lock.

These master controllers are modified somewhat in form to suit different requirements. Some provide for reversing by moving the controller handle in an opposite direction instead of by employing two separate cylinders as in the *K* controllers. Some provide for only two series and two multiple notches, the intermediate positions being cared for automatically.

Various Schemes of Acceleration.—The object of the control apparatus on a street car is to provide for the correct application of the power in suitable amount for starting, for moving forward

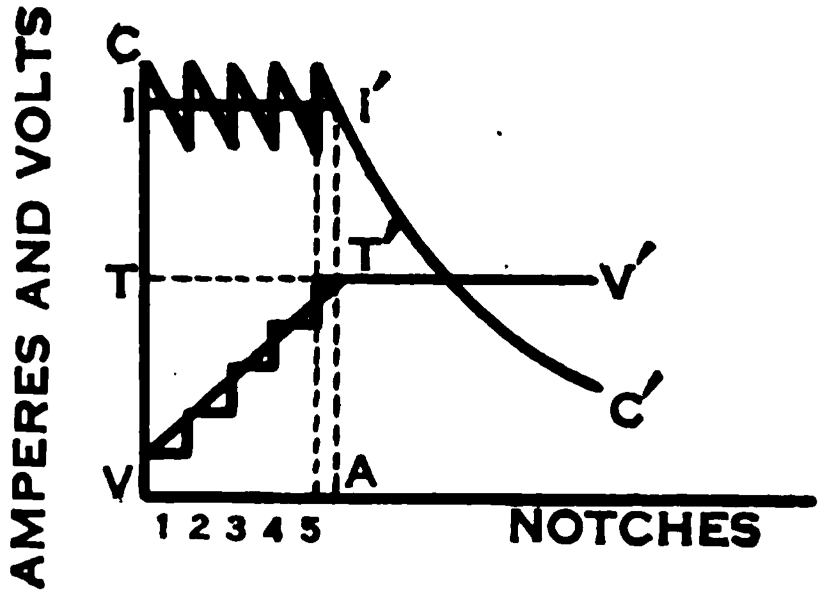


FIG. 1059.

or backward, for opening the power circuits and the protection of equipment. It is evident that it would be disastrous to apply full line current to the motors when just starting. Hence the introduction of resistance to limit the current.

Series resistors are made of cast-iron grids coated with aluminum paint to prevent corrosion. These grids are supported on iron rods, from which they are insulated by mica tubes. Mica washers also insulate the grids from each other wherever electrical separation is required. Fig. 1058 shows a standard No. 14 series resistor manufactured by the Westinghouse Company.

The controllers and resistors are designed so that with ordinary operation the voltage will increase in a very uniform manner, and the variation of current in the motors will be limited so that smoother acceleration will result. Fig. 1059 shows how the

current C-C' and the voltage on the motor, V-V', change as the controller is operated through the first five notches. While the current is increased slightly with each succeeding notch, the counter e.m.f. due to the rising speed promptly reduces it to the

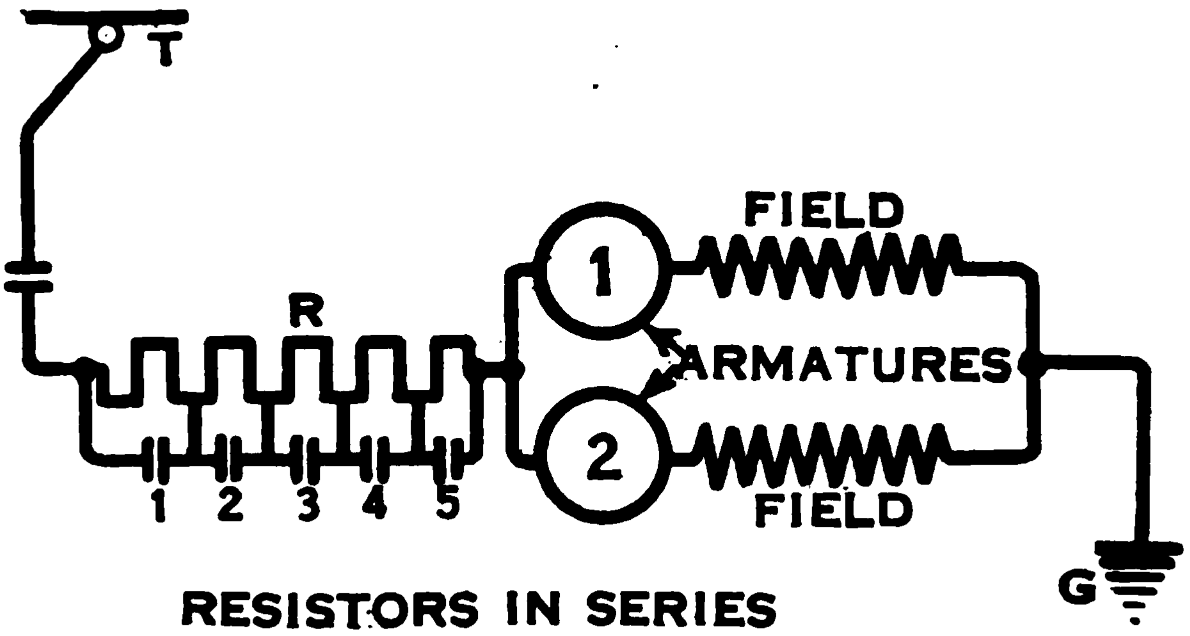


FIG. 1060.

lower value. For simplicity in calculation the current is assumed to have an average constant value of I-I'. The voltage on the motors notches up from V to T' in steps, but the voltage at which the current is taken from the trolley is constant at T-T'.

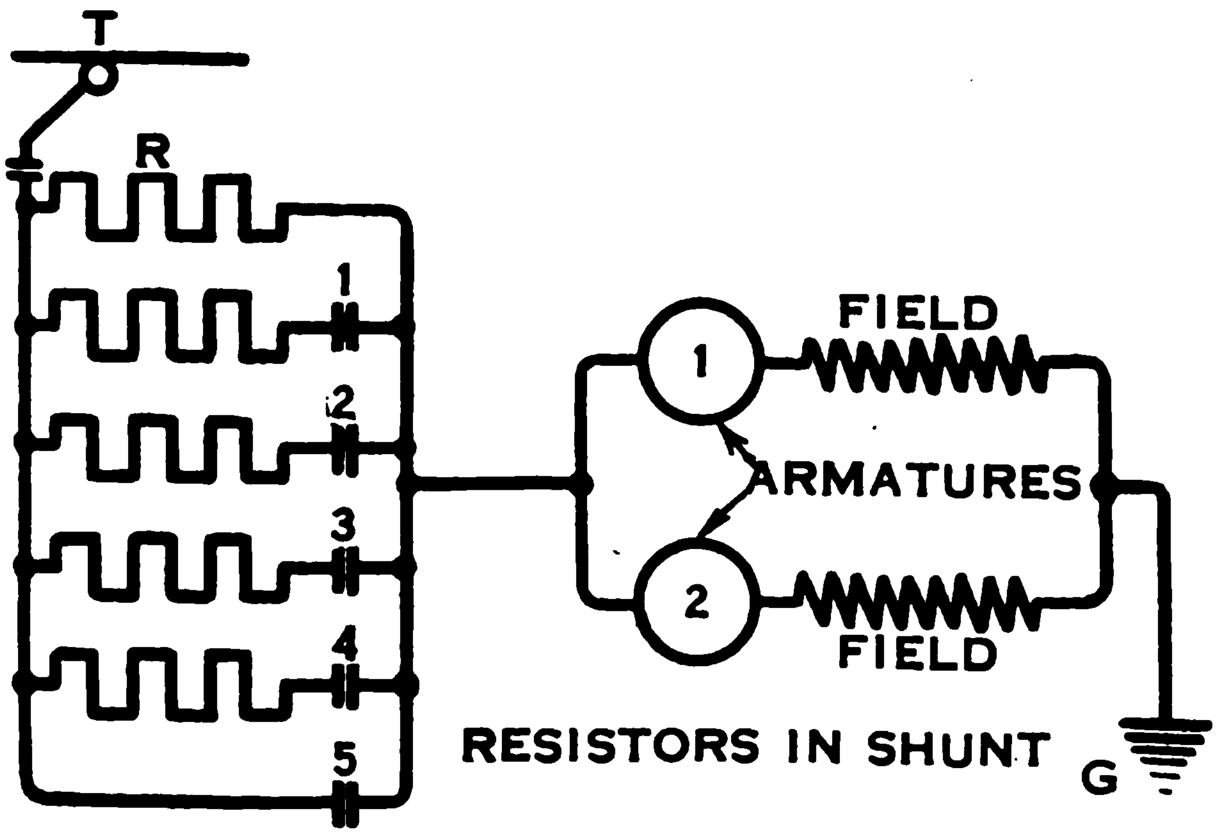


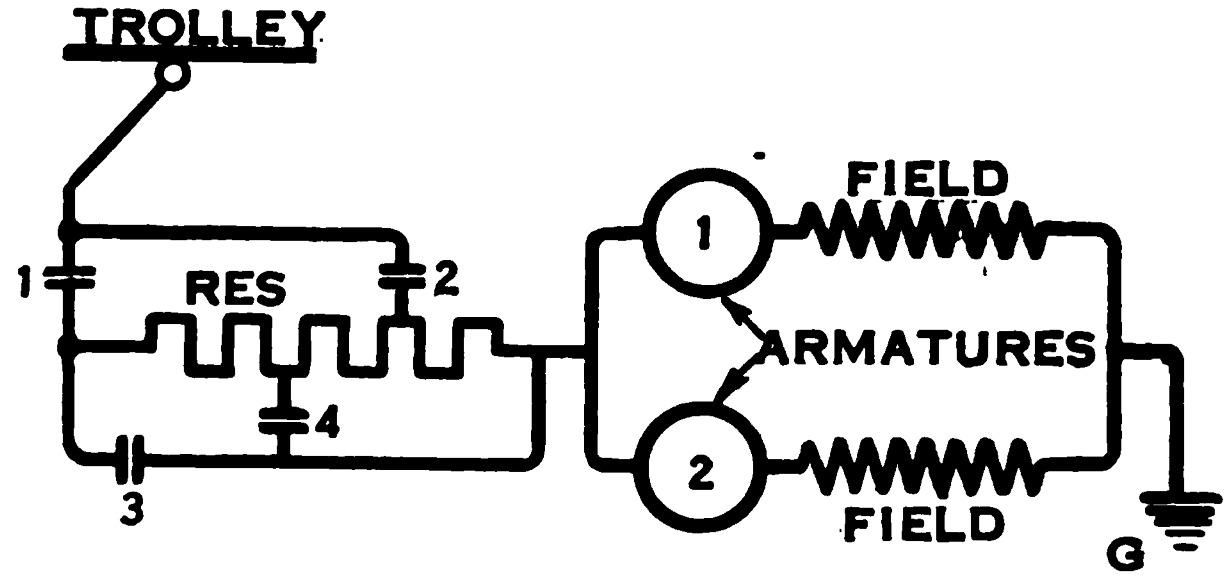
FIG. 1061.

The difference between the trolley and motor voltages is absorbed by the starting resistor.

Three classes of resistor connections are used in starting. **First,** with **series resistors,** all of the resistance is in circuit at start, and it is gradually short-circuited by sections as illustrated

in Fig. 1060. The switches which bring about short-circuiting of the sections are indicated at 1, 2, 3, 4 and 5. When power is first applied all the switches are open. They are closed consecutively as the controller handle is moved up until all are closed. In this position the motors are operating on full voltage without resistance in circuit, which is an economical operating condition.

The **second** plan is to use **parallel resistors** as in Fig. 1061. Here only a part of the resistor is in circuit at start, and additional sections are connected in parallel with the first section by successive notches until finally the entire resistor is short-circuited. Switches 1, 2, 3, 4, and 5 bring about this result.



RESISTORS PARTLY IN SERIES
AND PARTLY IN SHUNT

FIG. 1062.

When the last switch is closed the equipment is running at full line voltage.

The **third** class of resistor employs **combinations of** both **series and parallel** connections, as in Fig. 1062. The sequence of operation of the switches in this connection is as follows: On the first step switch 1 is closed. This puts the entire resistance in series. Next switch 2 operates, which short-circuits a section of the resistor. On the third step switches 2 and 3 only are closed. This places two portions of the resistor in parallel. On the fourth step switches 2 and 4 are closed. This reduces the combined resistance of the two sections, while on the fifth step 1, 2 and 3 are closed and all of the resistance is cut out.

It is essential, in passing from the series to multiple connections of motors, that the transition shall be effected smoothly

without possibility of short-circuiting and if possible without interruption of the application of power.

There are **three methods** of transition which may be used. They are known as the **Open Circuit** method, the **Shunting** method, and the **Bridging** method.

The **Open Circuit** method consists in opening the power circuit entirely in passing from series to parallel. This is illustrated in Fig. 1063, where *A* shows the last series notch with the motors in full series and the starting resistance cut out. *B* represents the transition where the power line is entirely

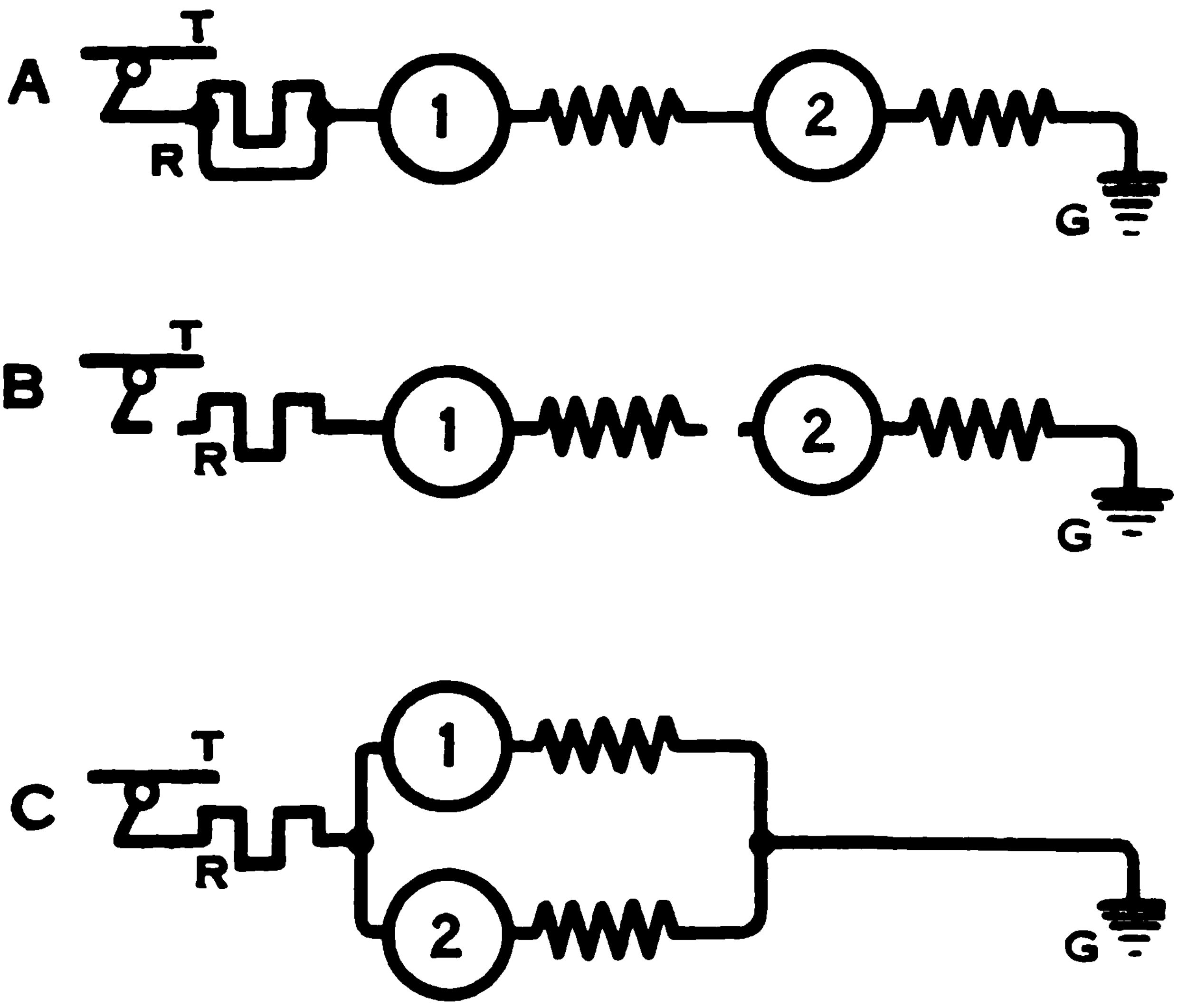


FIG. 1063.—"Open-circuit" method of transition from series to parallel connections.

opened at two points. *C* shows the motors thrown in parallel, the starting resistance being reinserted and the line closed. The **Type L** controller employed this method on large equipments. While many of these equipments are still in use, the plan is obsolete, having been replaced by the **Bridging** method used in connection with the **Type M** system of control.

The **Shunting** method is illustrated in Fig. 1064. The last series position is shown at *A*, and the first step in transition at *B*. Here the starting resistance is partially reinserted. In *C*, motor No. 2 is short-circuited. In *D*, motor No. 2 is removed from the short circuit and in *E* it is swung in parallel with motor No. 1.

This is the plan used on the K controller and is suitable for small and moderate sized equipments. While the power circuit is not opened in transition, motor No. 1 develops the entire torque, and motor No. 2 is idle while changing from series to parallel. This plan also includes the method of series resistors shown in Fig. 1060.

The **Bridging** method of transition is illustrated in Fig. 1065. On the last series notch shown at A, two sections of resistance

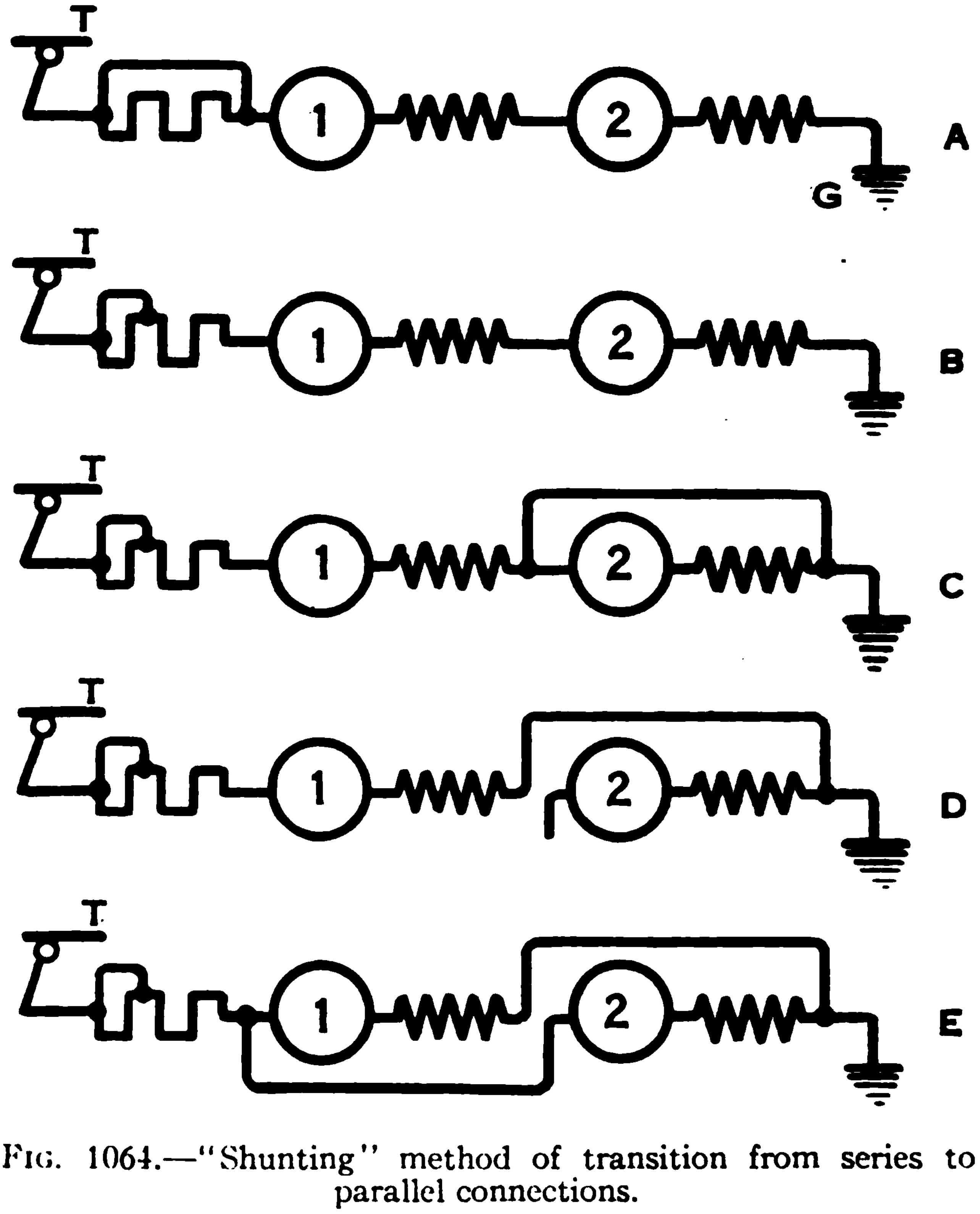


FIG. 1064.—"Shunting" method of transition from series to parallel connections.

are shown on open circuit at D and D'. The first step in transition consists in swinging the armature connection H, in figure B, around to the point D, which is a preliminary parallel connection. This does not appreciably alter the potential on this motor from that which it originally received through the connection E'-E. At the same time connection R' is swung around

to the ground point *G*, which grounds motor No. 1 without appreciably altering its potential. In diagram *C* the **bridge** or equalizer *E′-E* is broken, and the two motors are in parallel without the power circuit having been interrupted or the current removed from either motor. Full torque is thus maintained while in transition. The resistors are then again cut out as when the motors were first starting in series. This plan is the one commonly employed on large equipments such as the New York subway lines and insures a smooth acceleration while changing from series to parallel.

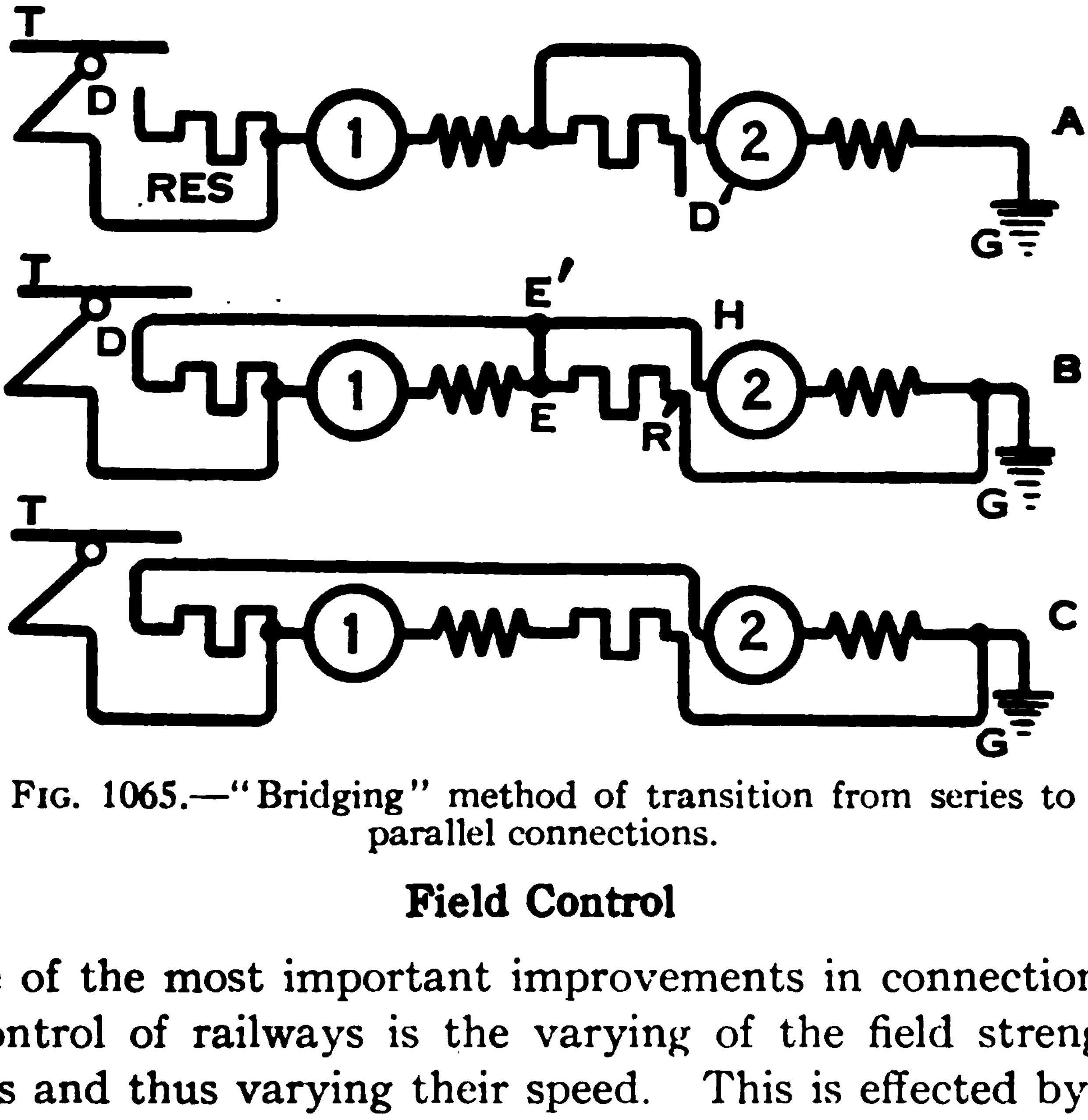


FIG. 1065.—"Bridging" method of transition from series to parallel connections.

Field Control

One of the most important improvements in connection with the control of railways is the varying of the field strength of motors and thus varying their speed. This is effected by using motors having a larger number of turns in the field winding than are ordinarily employed and by arranging the control so that on certain notches a portion of the field winding is cut out of circuit. This effects a saving in power consumption and gives a flexibility of operation in service. It permits the same equipment to be used in city running, which is at slow speed, and suburban running at high speeds. It also makes the same equipment adaptable for local running where there are frequent stops and to limited running between remote points where there are few stops. This scheme of control effects a considerable saving in power under these conditions.

When the entire field winding is in use the motor can produce large tractive efforts at slow speeds with a moderate current input. This enables it to start and accelerate a car very economically. When a portion of the field winding is cut out, the characteristics of the motor are modified just as if the gear ratio had been instantaneously changed.

The use of field control increases the efficiency of the equipment in starting by reducing the resistance loss. In Fig. 1066 the height of *A-B* and *C-D* above the base line indicates the currents taken per car from the trolley in series and parallel connections respectively without the use of field control. The area *O-A-B-C-D-E* is a measure of the total energy taken from

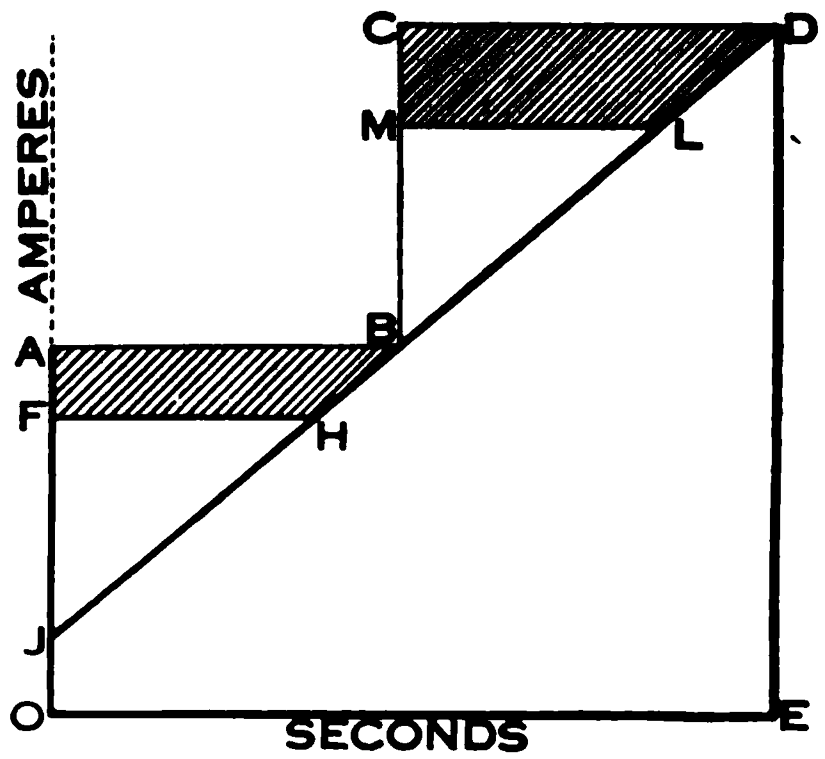


FIG. 1066.

the trolley in starting, and the area *O-J-B-D-E* represents the actual input to the motors, while the areas *J-A-B* and *B-C-D*, show the rheostatic losses. If field control is used, the currents are reduced to *F-H* and *M-L* with full field, but on the shunt field notches, where the field strength is reduced, they are at *B* and *D*. The total energy from the trolley is represented by the area *O-F-H-B-M-L-D-E*, while the energy delivered to the motors is the same as without field control *O-J-B-D-E*, and the rheostatic losses are shown by the area *J-F-H* and *B-M-L*. This shows that the rheostatic losses, and therefore the total energy taken by the car, are reduced by the amount indicated in the shaded areas *F-A-B-H* and *M-C-D-L*. In various tests

this reduction in energy consumption, brought about by the use of field control, has been found to be from 5 to 17% of the total energy taken by the car.

The H. Ward-Leonard System of Railway Control

The Leonard system of variable speed control for electric motors has a peculiar advantage when applied to the operation of a street car. While for certain reasons the system is not in practical use, the principle involved is worthy of careful con-

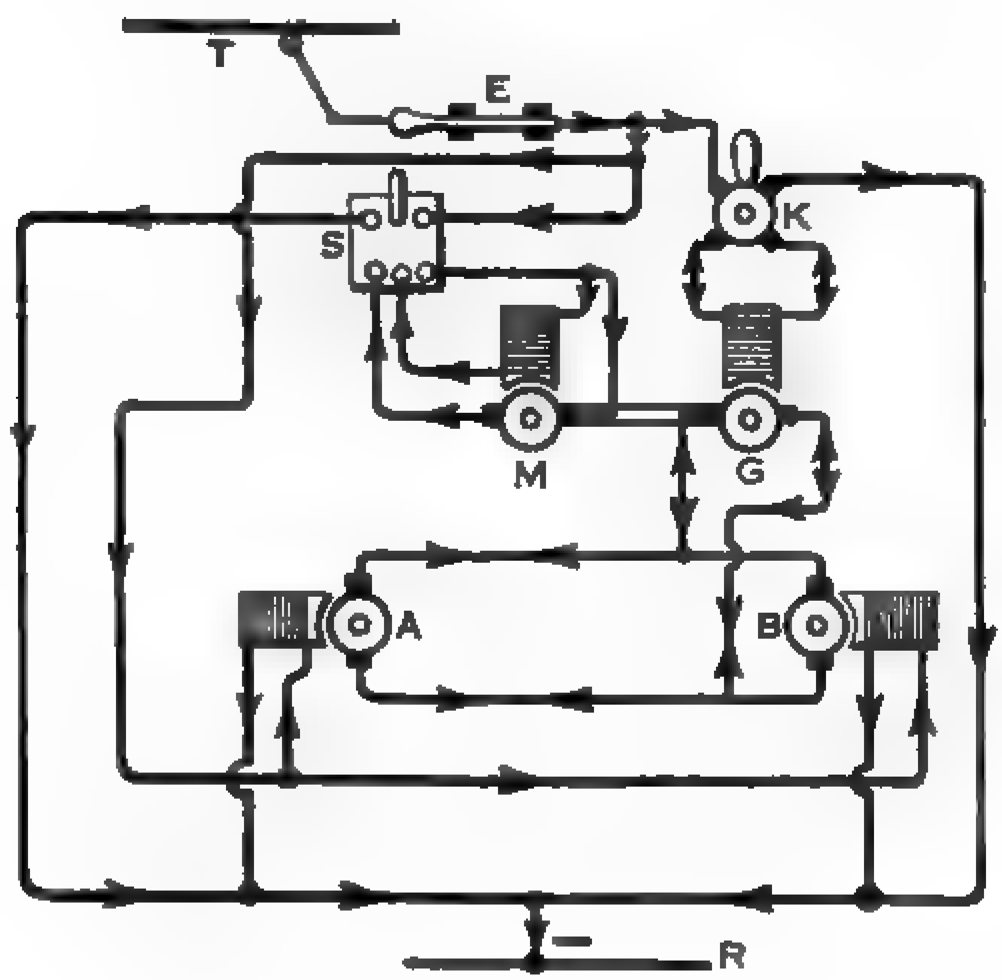


Fig. 1067.—H. Ward-Leonard system of control applied to electric car operation.

sideration. The plan requires the use of two gearless propelling motors, *A-B*, Fig. 1067, with separately excited fields, permanently energized at full strength from the trolley *T*. Beneath the car and between the axles there is supported a motor-generator set called the "power converter." The motor *M* is shunt wound and connected to the trolley through a starting box *S*. The field of the generator is connected across the line between the trolley and the rail and has inserted in it a regulating

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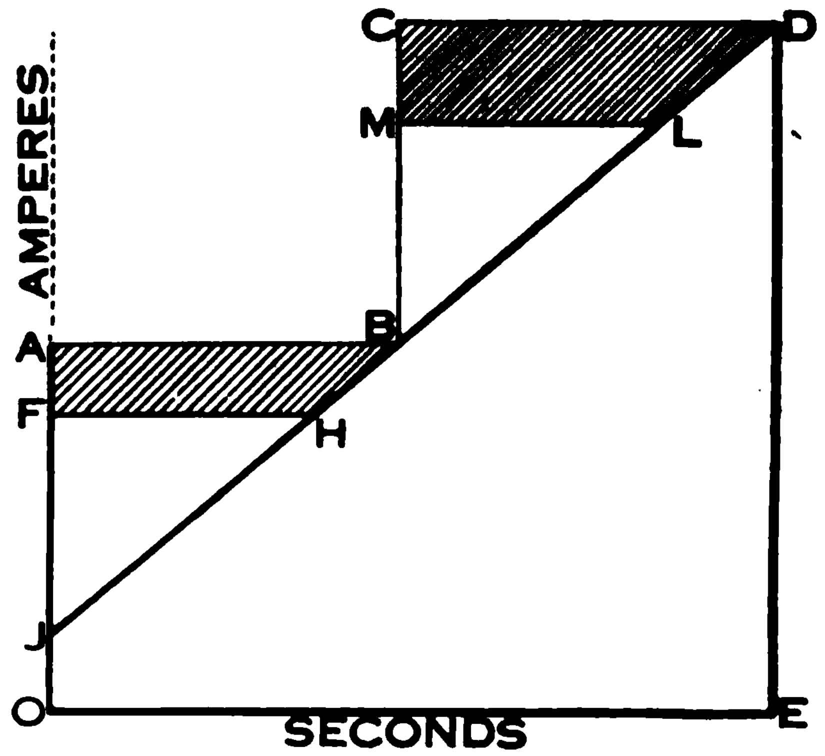

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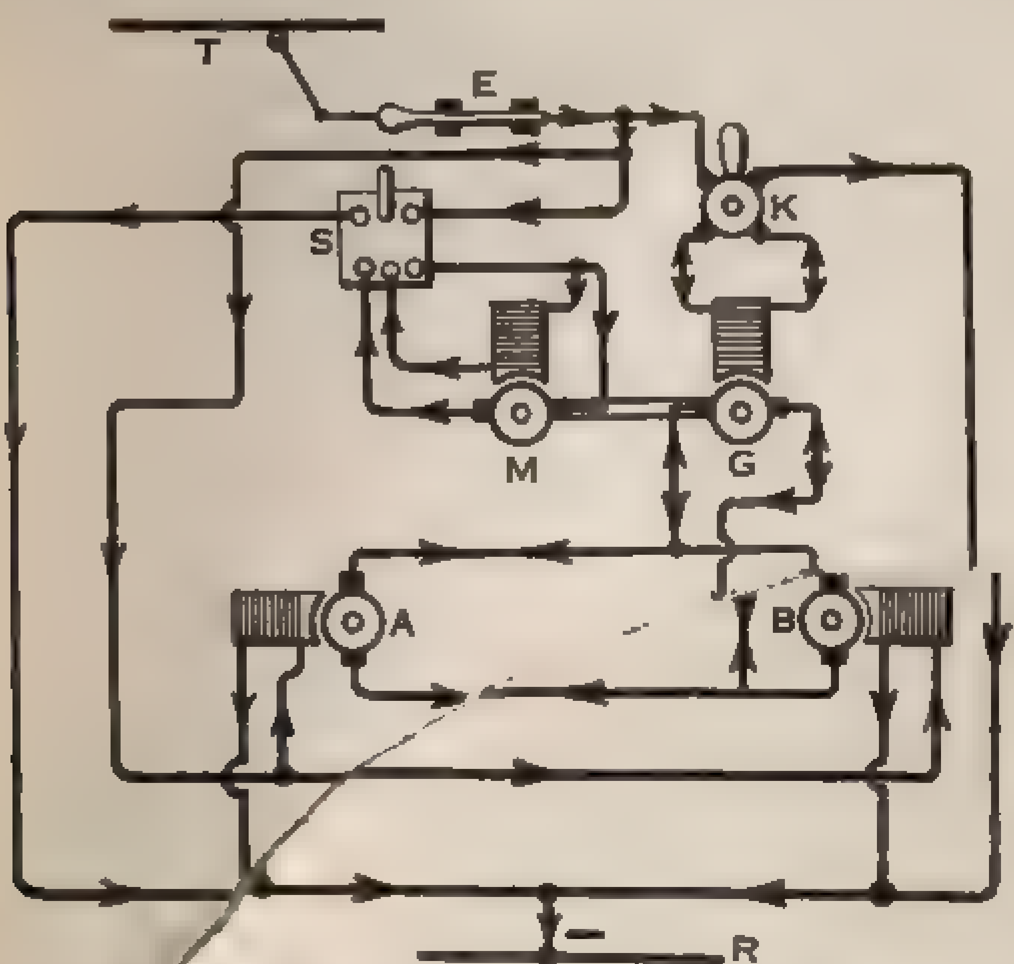

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and reversing field rheostat K. The armature of the generator G is connected in series with the armatures of the propelling motors, A-B, the latter two themselves being in parallel.

Consider the motor-generator set operating at full speed and the field rheostat of the generator in its open position so that the generator field circuit is broken. Although the generator armature is being driven at full speed, it is revolving in a field having no strength and hence produces no volts. If the field rheostat K is moved so as to place the generator field across the line and with a resistance in series with the field of ten times the resistance of the field coils, a slight excitation will result and perhaps 40 volts will be produced at the brushes. This voltage will develop a current through the armatures of the driving motors limited only by the ohmic resistance of this circuit, and hence at this low voltage a large current will be produced, which in a field of full strength will cause a torque sufficient to start the car. The speed of the armature will, of course, be governed by the counter e.m.f., which will be constant as long as the e.m.f. supplied is constant. If the field of the generator is now increased by cutting out resistance, the delivered e.m.f. will rise, and with it the speed of the driving motors. As these armatures revolve in a field of constant strength, the torque that they produce will be exactly proportional to the current which they receive. Thus it will be seen that the speed of the car will depend upon and be proportional to the e.m.f. supplied by the power converter, and the torque will be dependent upon the current supplied by the power converter. Suppose that 60 amperes passes through the armatures A-B and, in the fully excited fields, develops a sufficient torque to move the load upon a grade. It is probable that 40 volts from the power converter would produce this current. Hence by an expenditure of but 2,400 watts in the secondary circuit or a total including the allowance for all excitation and transformation losses of not more than 8 horse power, a fully loaded car could be started. Under ordinary conditions with series-parallel control, this same 60 amperes would be required to develop the necessary torque, but it would have to be drawn under the trolley pressure of 500 volts and would therefore represent a consumption of energy of 30,000 watts as against possibly 6,000 watts in this system. The current from the line in starting the car under

ordinary conditions by this system would only be about 12 amperes at 500 volts instead of 60 amperes at 500 volts.

In practice the regulating rheostat, which, of course, is exceedingly small because of the small amount of power which it handles, may be thrown at once from its "off" position to the extreme position for full speed. The field magnetism of the generator rises smoothly, and with it the e.m.f. which causes a gradual acceleration of the car.

If, while running at full speed, the field of the generator is weakened by the rheostat K, the applied voltage falls and the counter e.m.f. of the propelling motors A-B exceeds that of the generator. The momentum of the car will now be driving the gearless motors as generators which will supply current to the former generator operating it as a motor, causing it to drive the shunt motor as a generator which will raise its counter e.m.f. above the trolley and thus deliver energy back to the line. This will act as a brake and smoothly and rapidly bring the car to rest. By setting the field rheostat at any desired point, a car on this system may be made to descend a grade at any speed, regenerative braking being entirely under the control of the small field rheostat which governs the speed, the braking and the direction of the car, for it is only necessary to reverse the current in the field of the generator to reverse the direction of the delivered current to the armatures A-B. As the fields of the propelling motors are of fixed strength and direction, the direction of the car is reversed whenever the current in the armatures is reversed. This reversal is effected, however, without any switches in the circuit of the armatures themselves, being wholly controlled by the current in the field of the generator through K. With this system it would not be necessary to equip cars with more than one-fifth of the present horse power in motors, as the smaller horse-power equipment is in effect connected to the trolley through a great gear reduction, and by means of the field control of the generator the ratio of this gearing is automatically and smoothly changed. One disadvantage of this system lies in the fact that every car must have an equipment consisting of a constantly running motor-generator set equal in capacity to that of the propelling motors which drive the car.

SECTION XX CHAPTER II

ELECTRIC RAILWAYS

CONTROLLERS

1. (*a*) Explain the general scheme of series-parallel control for street railway motors.

(*b*) What are its advantages and disadvantages?

2. What are the special features involved in the General Electric Type K controller?

3. What are the special features involved in the General Electric Type L. controller?

4. What are the special features involved in the General Electric Type R controller?

5. What are the special features involved in the General Electric Type B controller?

6. What are the special features involved in the General Electric Type M control?

7. What are the special features involved in the General Electric Type C controller?

8. Explain in detail the plan of the K2 controller showing what is accomplished on each step.

9. Explain in detail the plan of the K35 controller showing wherein it differs from the K2.

10. (*a*) Explain the principle of the "magnetic blow-out."

(*b*) Is it necessary on street-car controllers? Why?

11. In accelerating a car, what three general plans of connecting resistors in circuit may be employed? Explain each.

12. In changing motors from series to parallel connections, what three methods of transition may be used? Explain each.

13. Explain the method of "field control" employed on certain railway equipments. When and where is it advantageous?

14. (*a*) Explain the H-Ward-Leonard system of control for street railway motors. What are its advantages and disadvantages?

ELECTRIC RAILWAYS

ELECTRIC LOCOMOTIVES

The electric street car has been gradually increased in size until it has become suitable for high-speed suburban and interurban work operating singly, or a number of cars may be operated in multiple, or one motor car may haul one or more trailers. Large size units may be operated as locomotives upon which no passengers are carried, but equipped with motors of sufficient power to produce the required draw-bar pull and of sufficient weight to develop the necessary tractive effort to propel trains of any size at any desired speed.

Locomotives are of two types: First, those designed for slow speed operation in freight service usually of great weight, geared for approximately 20 miles per hour and designed for producing large tractive efforts. Second, those designed for passenger service, geared for speeds of 60 to 70 miles per hour with sufficient tractive effort for Pullman trains of maximum size.

With reference to the current supplied they may be either D. C. or A. C. The first locomotives were designed for D. C. Voltages of 600, 1,200, 2,400 and 3,000 have been successfully employed commercially and 5,000 volts has been successfully used experimentally.

Alternating-current systems have been devised which employ trolley pressures of 1,000, 6,600, and finally 11,000 volts. For D. C. service the series-wound motor has invariably been used. This type of motor has been perfected in single units in sizes ranging from 40 horse power up to 2,000 horse power. Alternating-current motors are either of the series-wound commutating type, similar to the D. C. motor except that the field cores are laminated, or of the three-phase induction type with wound rotors.

Electric locomotives have been developed by the cooperation of the two large locomotive companies and the two large electrical companies. The general Electric Company in cooperation with the American Locomotive Works, and the Westinghouse Electric and Manufacturing Company, in cooperation

with the Baldwin Locomotive Works, have both developed a variety of alternating and direct-current locomotives.

Various methods of transmitting the power from the motor to the axle have been perfected. Fig. 1068 shows the method of mounting and gearing used in cars for city and suburban traffic. The motor *M* is geared from a pinion *P* through a single reduction to the gear wheel *G*. The center of gravity is low and the arrangement is entirely satisfactory in moderate sizes up to equipments of 500 horse power operating at speeds of 40 and 50 miles per hour.

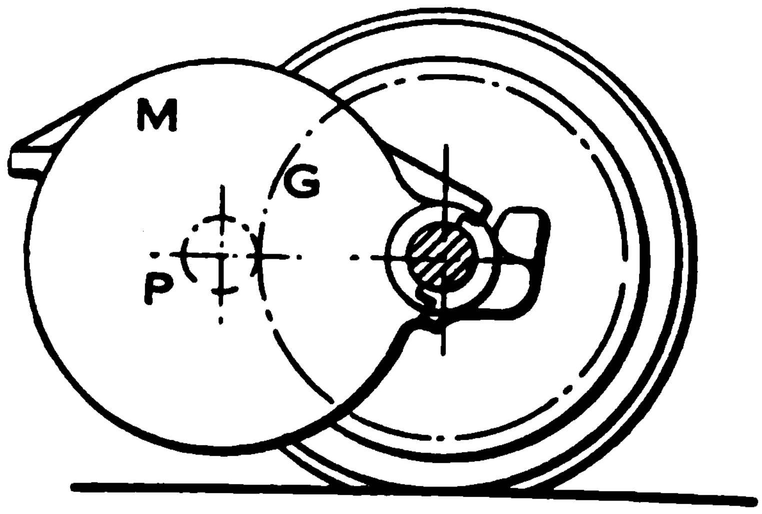


FIG. 1068.—Direct geared motor drive; single reduction.

Fig. 1069 illustrates the plan employed by the New York, New Haven and Hartford in the Westinghouse-Baldwin alternating-current locomotives, in the No. 071 type, operating between New York and New Haven, Conn. The motor *M* is mounted directly over the axle, a pinion, *P*, on the shaft engaging a gear, *G*, which is mounted on a tube or quill, *T*, which surrounds the axle but is 2 inches larger

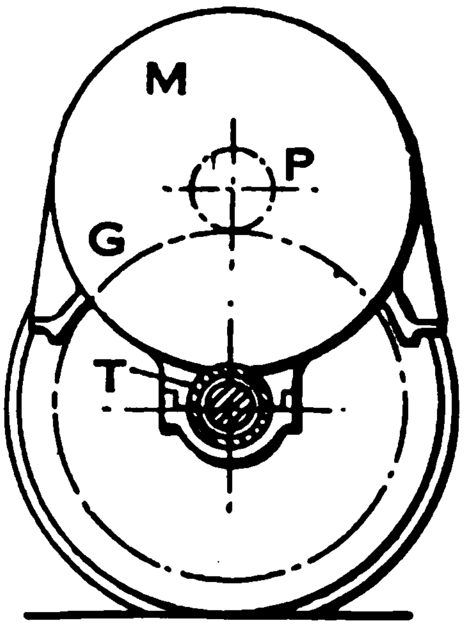


FIG. 1069. — Single armature gear and quill drive.

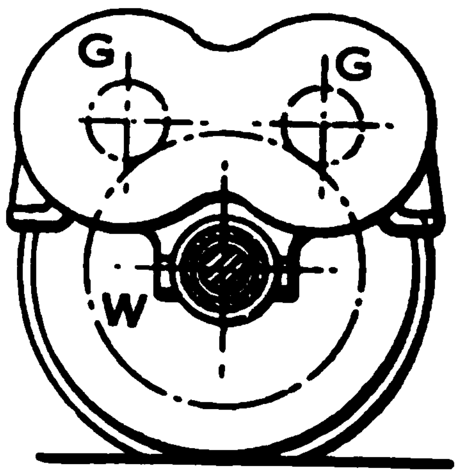


FIG. 1070.—Twin armature gear and quill drive.

in diameter so as to admit of a vertical play for the spring supported motor and gears.

Fig. 1070 represents the method of gearing used on some of the Westinghouse motors of the Chicago, Milwaukee and St. Paul equipments. Here the two armatures of the twin-motor

equipments connect through separate pinions *G-G* with a gear wheel *W* carried on a quill as in the preceding case

Fig. 1071 represents the plan adopted in the Norfolk and Western equipment where two motors, *M-M'*, engage through separate pinions on a gear wheel, *G*, carried on a counter-shaft,

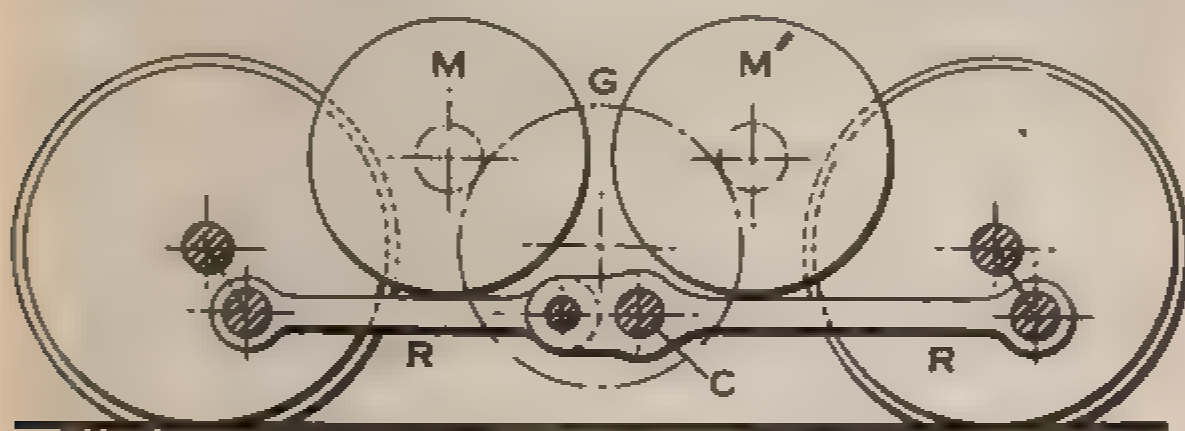


Fig. 1071 —Gear and side-rod drive

the whole being attached to the framework of the locomotive and therefore spring supported By means of a crank *C* on this counter-shaft, connecting rods *R-R* transmit the power to cranks on two driving wheels on the locomotive

A radical design in locomotive construction is shown in Fig 1072. This represents the New York Central direct-current

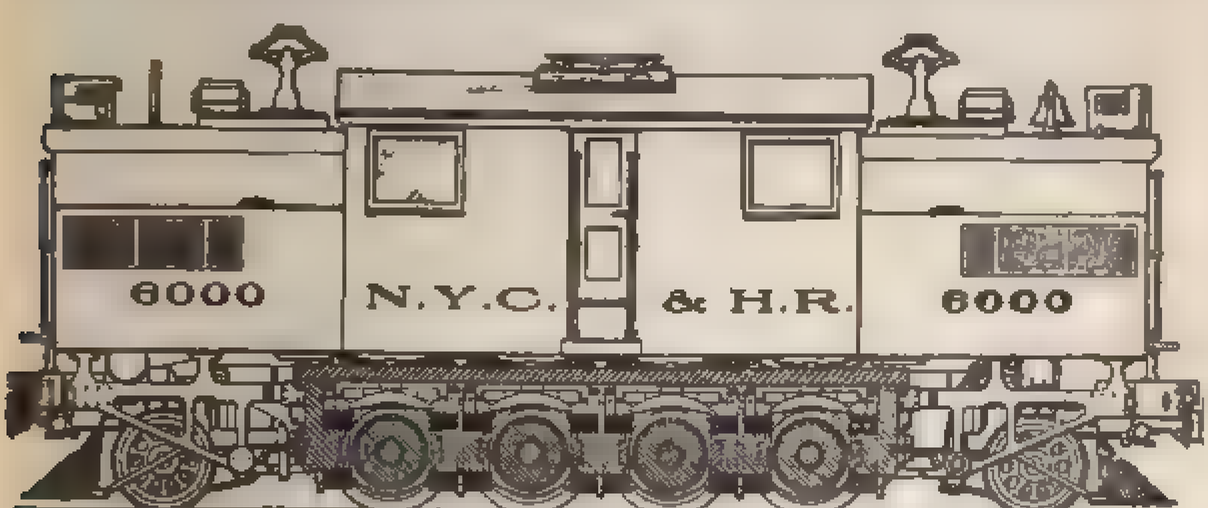


Fig. 1072. Original gearless New York Central 600-volt direct current locomotive

600-volt locomotive which carries four General Electric 550-horse-power bi-polar gearless motors. The armatures are carried solidly on the driving axles The fluxes pass through all four motors in series magnetically The air gap is sufficiently

large to allow the armature to drop out when the body of the locomotive is jacked up, which makes access in case of repair extremely simple These locomotives develop a maximum of 3,000 horse power and weigh 95 tons each, 69 tons of which is carried on the drivers They develop a maximum draw-bar pull of 32,000 pounds and will haul a 500-ton train 60 miles per hour. An objection to this construction in the first locomotives of this type was the severe pound on the road bed and the low center of gravity which causes "nosing." This tended to

FIG. 1073. Latest type of 600-volt New York Central gearless locomotive, built by the General Electric Company.

spread the tracks and derail the train Fig 1073 illustrates a later form of this locomotive with a four-wheel pilot truck attached at each end This was found to be an improvement, as it counteracted the nosing tendency and guided the main section of the locomotive successfully The simplicity and success of this design in practice have warranted its radical features.

The Westinghouse-Baldwin locomotives designed for the Pennsylvania Terminal electrification represent another unusual construction These locomotives are of 4,000 horse power designed for direct current at 600 volts. They are 65 feet in

length, weigh 166 tons, of which 104 tons is carried on the drivers They exert a maximum draw-bar pull of 60,000 pounds and are designed for a speed of 70 miles per hour The locomotive is built in two sections, each section containing one 2,000-horse-power motor with field control. The motor is mounted well up in the cab and carries on each end of its armature a crank, the two cranks being placed at 90° with respect to each other. The method of drive is shown in Fig. 1074. The motor *M* connects from its crank through a connecting rod *C*, with a crank on a jack shaft *D*. This shaft, together with the motor, is carried on the spring-supported frame of the locomotive, while the driving wheels *E* and *F* run rigidly on the track. Thus while the counter-shaft, *D*, and the motor may rise and

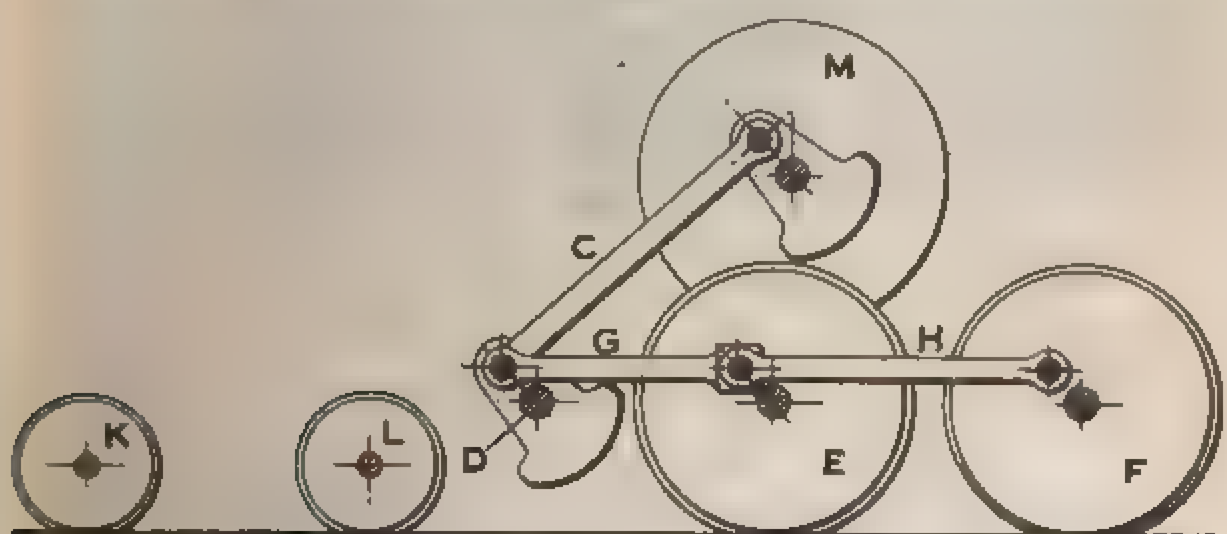


Fig. 1074 —Plan of side-rod and crank drive employed in the "Pennsylvania" type of locomotive

fall vertically through a limited range, they connect rigidly through the connecting rods *G* and *H*, with the cranks on the driving wheels, and there is sufficient play in the boxes which carry the bearings for the driving wheels, to admit of the slight change in radius necessary as the shaft *D* moves up or down with respect to the axles of the driving wheels These drivers are 68 inches in diameter, while the wheels of the pilot truck *K* and *L* are 36 inches in diameter. Fig. 1075 shows the appearance of the motors and running gear for this locomotive without cab. The appearance of the complete locomotive is shown in Fig. 1076. Fig 1077 shows one of these locomotives hauling a passenger train out of the tunnel and about to enter the Pennsylvania Station in New York City.

FIG. 1075. Running gear of "Pennsylvania" type direct current electric locomotive showing position of the two 2,000-h.p. motors and side-rod drive.

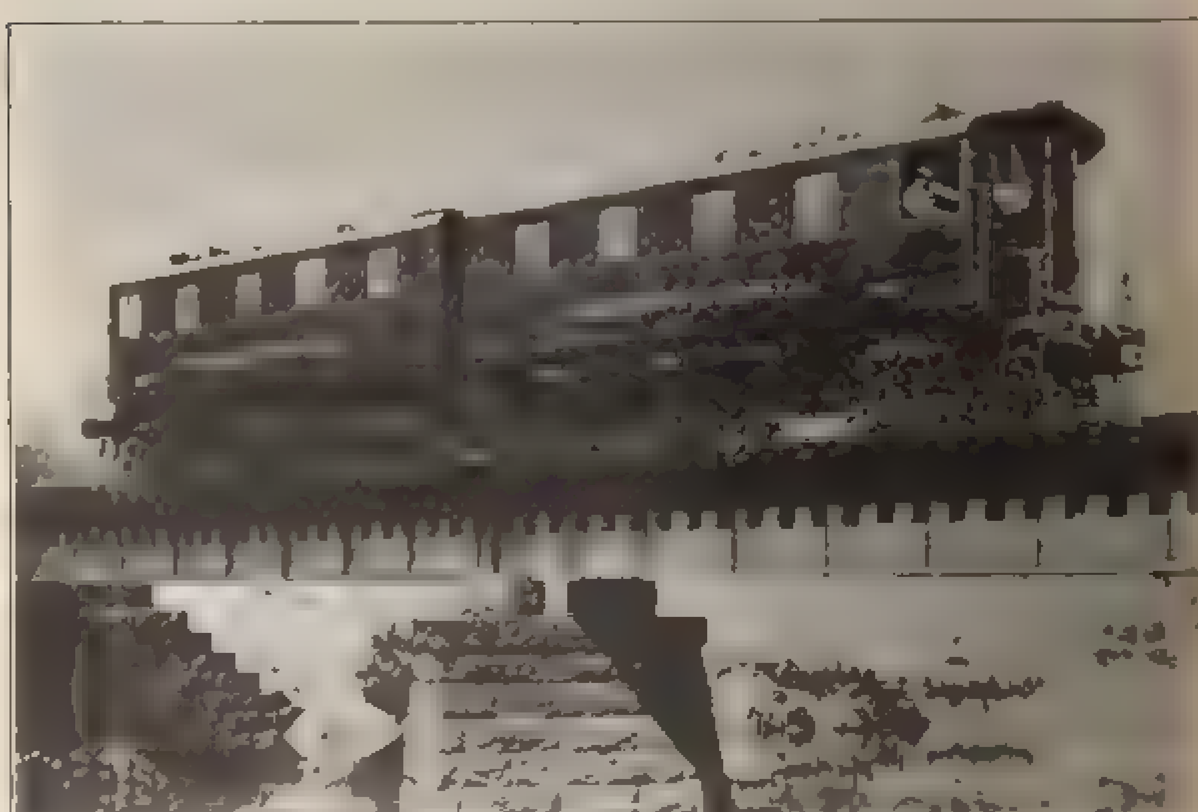


FIG. 1076.—"Pennsylvania" type of direct current locomotive designed to develop 4,000 h.p. at 600 volts, Westinghouse-Baldwin construction.

FIG. 1077 Westinghouse Baldwin "Pennsylvania" type 600 volt direct-current locomotive, hauling Pennsylvania train from tunnel into Pennsylvania station in New York City

FIG 1078 Single phase Westinghouse Baldwin alternating current locomotive operating on 11,000-volt trolley, New York, New Haven & Hartford Railroad

Fig. 1078 shows the general appearance of one of the No. 071 type, New York, New Haven and Hartford locomotives. These operate at a trolley pressure of 11,000 volts, this e.m.f. being reduced by means of a transformer carried on the locomotive, to approximately 325 volts for the series-wound, compensated, commutating A. C. motors. This voltage was adopted in order to reduce commutating difficulties to a minimum and so that the motors may operate in the direct current zone entering the Grand Central Station on the 600-volt D. C. circuit, the virtual voltage of the A. C. being 70% of that of the D. C. One locomotive carries four motors of 375 horse power each, and is capable of hauling an 800-ton train 45 miles per hour. Fig. 1079 shows a sectional view of this locomotive. Each motor is connected to its respective set of drive wheels through twin spur gears, quill and helical springs. The latter are shown in connection with motor No. 1. The master control apparatus, meters, air brake valve, sanding foot lever, etc., are in duplicate at either end of the cab, and jumper connections are provided for multiple operation of locomotives from a single master controller. To economize space the main air reservoirs are mounted on the roof of the cab, at either side of the alternating-current pantagraph trolleys. There are two distinct trucks on which the single cab is carried.

The Norfolk and Western locomotives designed by the Westinghouse company are illustrated in Fig. 1080. They employ single-phase power delivered from an overhead trolley to the locomotive at 11,000 volts and 25 cycles. The scheme of electrical connections is illustrated in Fig. 1081. The current is stepped down to 725 volts through a transformer carried on the locomotive. At this pressure it is delivered to a **Phase Converter,** C, which is virtually a two-phase induction motor with a cage-wound rotor. One winding, *A*, of this phase converter is connected across the terminals of the secondary of the transformer. This induces current in the rotor, *R*, which in turn reinduces current back in the phase *B*, which is 90° mechanically away from phase *A*. This second current is fed into the middle of the secondary of the transformer at the point *D*, thus enabling three-phase currents to be drawn from the points *H*-*G*-*B*. This in effect constitutes a Scott connection, and the three-phase currents so obtained are employed to operate the propelling

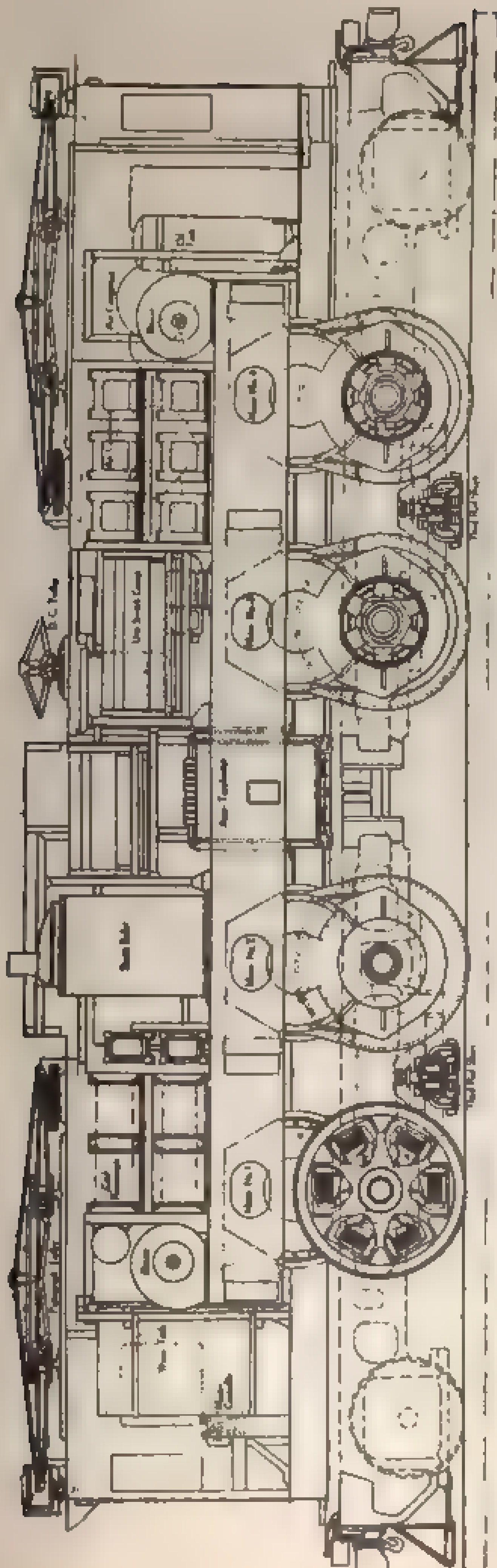


FIG. 1079.—Sectional view of locomotive pictured in Fig. 1077, showing location of motors.

motors *M*. There are four of these motors of 400 horse power each, designed for 725 volts, with form-wound rotors and three slip rings. These motors are mounted as shown in Fig. 1071. A line drawing of this locomotive is shown in Fig. 1082. The locomotive is designed for speeds of 14 and 28 miles per hour. The propelling motors are connected in cascade with each other for slow speeds, the last motor in the cascade having its rotor connected to a liquid rheostat. The phase converter *C*, is of 1,500 K.V.A. capacity and is started by a small starting motor

FIG. 1080.—Single-phase Westinghouse-Baldwin locomotives with induction motors and side rod drive, on Norfolk & Western Railway.

which is of the straight, series-commutator type of liberal design. The multiple unit system of control is provided for the independent operation of each locomotive or for the simultaneous control of two locomotives from either end.

A similar type of locomotive built by the Westinghouse Company for the Pennsylvania Railroad is shown in Fig. 1083. It is known as the type F F 1 Pennsylvania and is designed to take current at 25 cycles from an 11,000-volt single-phase trolley wire. Power is transformed by means of a static transformer carried on the locomotive together with a phase converter, and is delivered through "Scott connections" to three-phase propelling

motors of the induction type at 850 volts. There are four of these motors. Each has six poles and a wound rotor. They

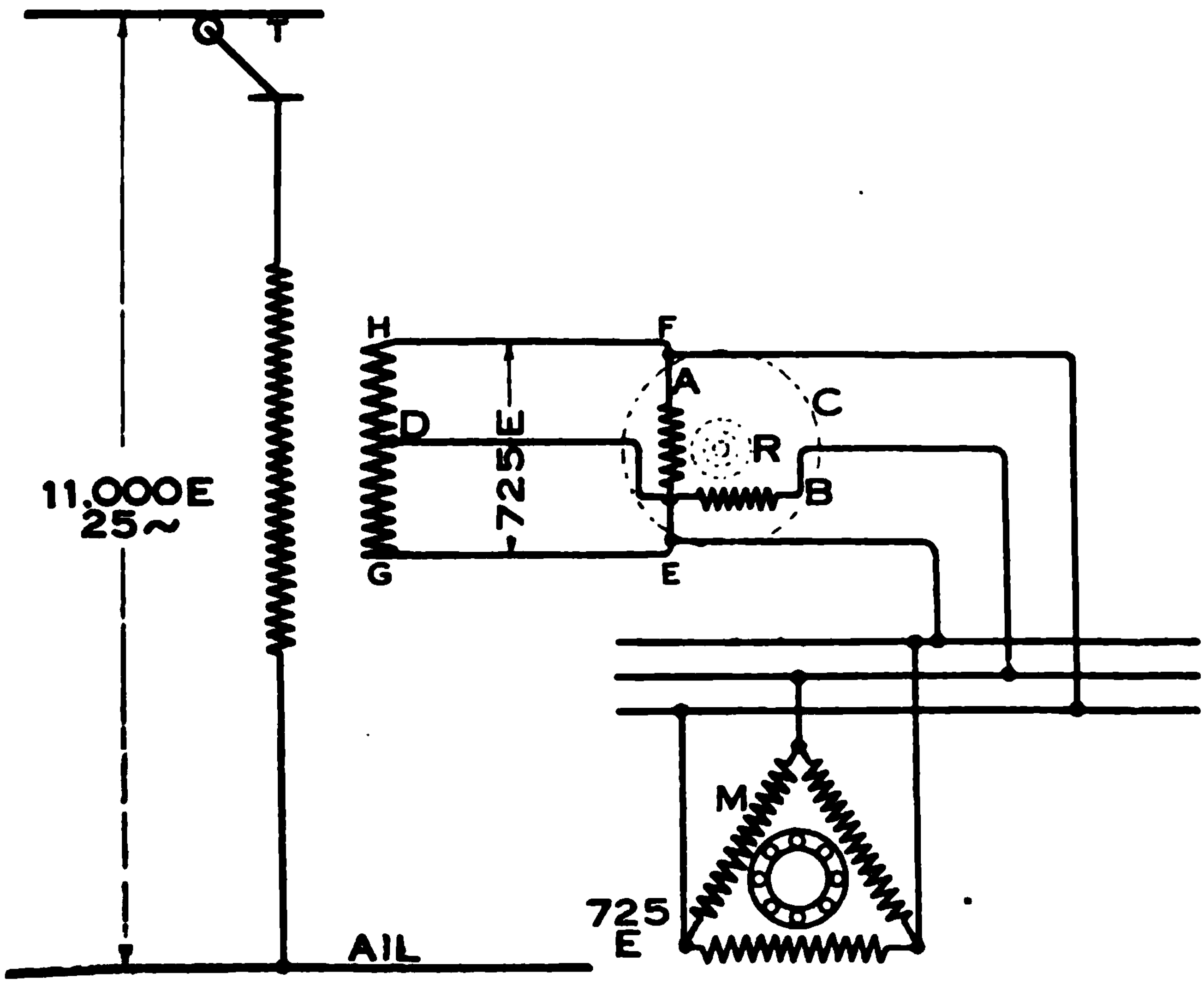


FIG. 1081.—Scheme of connections for Norfolk & Western locomotives showing power-converter which takes current from a single-phase source and converts it into three-phase for induction propelling motors.

drive through flexible jack shafts and side rods to driving wheels, 72 inches in diameter. The acceleration is by means of liquid rheostats in the rotor circuits. With the secondaries short-

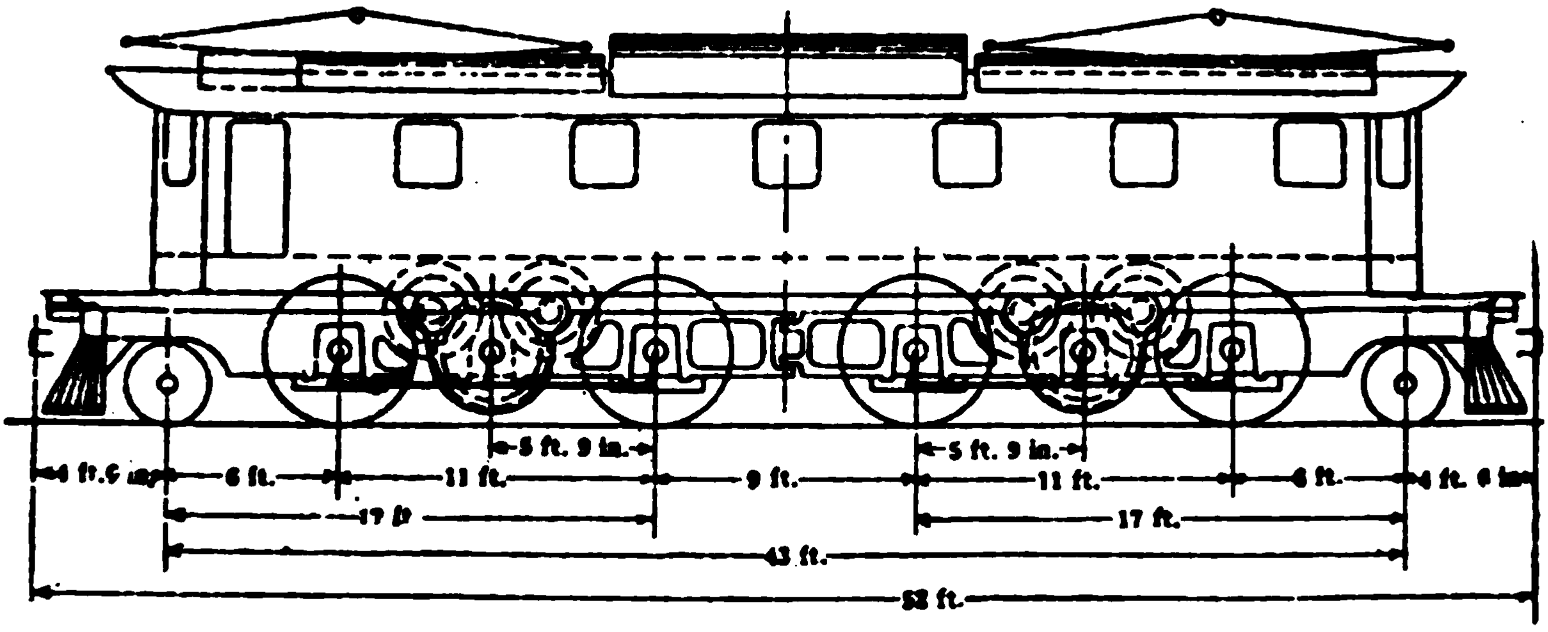


FIG. 1082.—General dimensions and location of motors on Norfolk & Western locomotive pictured in Fig. 1080.

circuited a maximum speed of 20.5 miles per hour is obtained. They are specially designed for freight service and develop

4,800 horse power for one hour with a maximum tractive effort of 140,000 pounds at the draw bar.

Most interurban lines are operated at 600 volts D. C. with a third rail, as on the Long Island electrification, or with 600 volts 1,200 volts and upwards from an overhead trolley. A departure from this practice is found, however, in the Philadelphia-Paoli electrification of the Pennsylvania Railroad Company. This line extends 21 miles west from Philadelphia and starts at the Broad Street Station. Power is transmitted from Philadelphia at

FIG. 1083.—Single phase Westinghouse-Baldwin locomotives operating at 11,000 volts on Pennsylvania Railroad.

44,000 volts to substations where it is stepped down to 11,000 volts, at which pressure it is employed on the single-phase overhead trolley. A transformer on the car steps this 11,000 volts down to 375 volts for each motor. Steel cars operated in trains form the equipment. Each car carries two 225-horse-power forced ventilated motors mounted on one truck. The motors are of special design by the Westinghouse Company and are of the series-repulsion type. They start as repulsion motors and, after attaining a speed of from 12 to 15 miles an hour, are changed over to operate as series motors. They are geared to the axle in

the usual manner except that the gears are flexible—that is, the torque of the motor is transmitted from the teeth to the axle through cushioning springs. This reduces the vibrations due to frequency changes and also reduces the shock on the gears and pinion. The control equipment is of the Westinghouse electro-pneumatic type arranged for the automatic acceleration of the motors.

SECTION XX CHAPTER III

ELECTRIC RAILWAYS

LOCOMOTIVES

1. **Explain the general construction**, scheme for mounting motors, and plan of drive employed in the N. Y., N. H. & H. electric locomotives.

2. **Explain the general construction**, scheme for mounting motors and plan of drive employed in the N. and W. electric locomotives.

3. **Explain the general construction**, scheme for mounting motors and plan of drive employed in the N. Y. Central electric locomotives.

4. **Explain the general construction**, scheme for mounting motors and plan of drive employed in the Pennsylvania terminal locomotives.

5. **Explain the kind of power** and voltage supplied from the trolley, the voltage and type of motors, method of control, advantages and disadvantages of the N. Y., N. H. & H. system.

6. **Explain the general scheme** of the "phase converter" used on the N. & W. electric locomotive, voltage and nature of power supplied from trolley, voltage and type of motors, method of control and general advantages of this system.

7. **Explain the general scheme** of the N. Y. Central system; nature and voltage of current supplied by trolley; method of control and general advantages of system.

8. **Explain the general scheme** of the Pennsylvania terminal system in New York City; voltage employed; nature of current; methods of control and general advantages of system.

ELECTRIC RAILWAYS

MULTIPLE-UNIT SYSTEMS

The acceleration of a train hauled by a single locomotive must necessarily be slow. For operating two locomotives together or for the rapid acceleration of trains in subways and electrified trains subject to frequent stops with several cars, it is desirable to operate all of the units simultaneously. **The multiple-unit** system of control was devised by **Frank Sprague.** The earliest types have been abandoned and the refinements that have been introduced have resulted in the application of the principle in three different ways.

The first successful scheme was the **Sprague-General-Electric Type M** system of control. This consisted of a bank of 13 electro-magnetic switches or contactors designed to produce all of the series-parallel combinations effected by the old cylindrical controller. The control outfit weighs about 2,000 pounds for each car. There are two distinct circuits, both taken from the 500-volt supply. One is the **control circuit** for actuating the contactors. This current is led through a small master controller designated by the letter C. The control current required for the contactors is $2\frac{1}{2}$ amperes per car. The operating coils are wound for 600 volts and will operate when the pressure falls as low as 300 volts. The **power circuit** leads to the motors through the contactor switches. The contactors are built on the plan shown in Fig. 1084. The control circuit passes through the energizing coil C. The power circuit is led through the armature and contacts via the line *P-P*. Each contactor is provided with a magnetic blow-out coil *B*, which ruptures the arc by means of the flux developed by the very same current which produces the arc. The actual appearance of a General

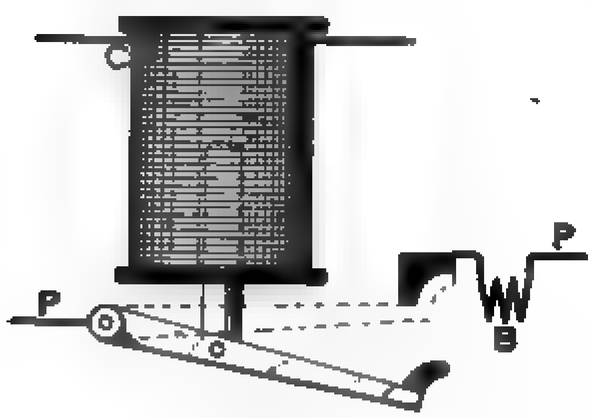


FIG. 1084.—Principle of electro-magnetic contactor.

Electric contactor is shown in Fig 1085. There are nine wires in the train line. The power circuit is illustrated in Fig 1086. To insure that current will never be maintained in the motor circuit through the sticking of any single contactor switch, three switches

Fig. 1085 Actual appearance of General Electric direct current contactor with interlock

are provided in series at all times so that, in case one or even two switches stick shut, the remaining one will open the circuit Each

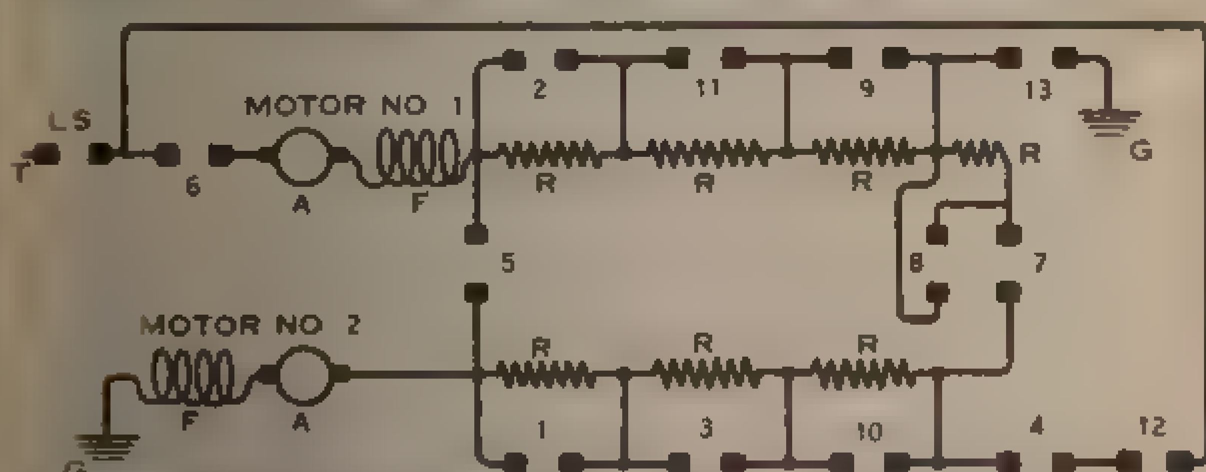


Fig 1086. General plan of power circuits for multiple unit control of two-motor equipments employing 13 electro magnetic switches

of these switches is so proportioned as to be able to rupture the maximum current drawn by the motors

The bridging system of transition from series to parallel is

employed on equipments of this sort The control circuit provides at start for the closing of the line switch *L-S* and contactors 6 and 7 Interlocks are provided to insure the operation of the switches in the proper sequence The starting resistance *R* is cut out gradually by the operation of switches 1-2-3-11-10-9 and 8. When this point is reached switch 5 is closed and the other switches drop open The diagrammatical sketch of the circuits provided by the operation thus far is shown in Fig 1087, *A*, *B* and *C* The change from series to parallel is now effected as in *A*, Fig 1088, by placing a ground at *G* on motor No. 1 and connecting the trolley at *T* on motor No 2. This is accomplished by the operation of contactors 13-12 and 4 The fall in potential between the trolley and ground through motor No. 1 and starting resistance is divided in half. The same is true of the division of potential in the circuit through motor No. 2. There is practically no difference of potential, therefore, across the bridge *D-E* In *A*, Fig. 10. 8, the motors are now in parallel, while in *C*, Fig 1087, they were in series. The parallel connections have been established without opening the power circuit or reduction in torque on either motor. The bridge *D-E* may now be removed This is done by opening switch 5 The resulting condition is shown in *B*, Fig 1088. The notching up of the motors to the full parallel position shown in *C*, Fig 1088, is accomplished by the successive operation of switches 1-2-3-11-10 and 9

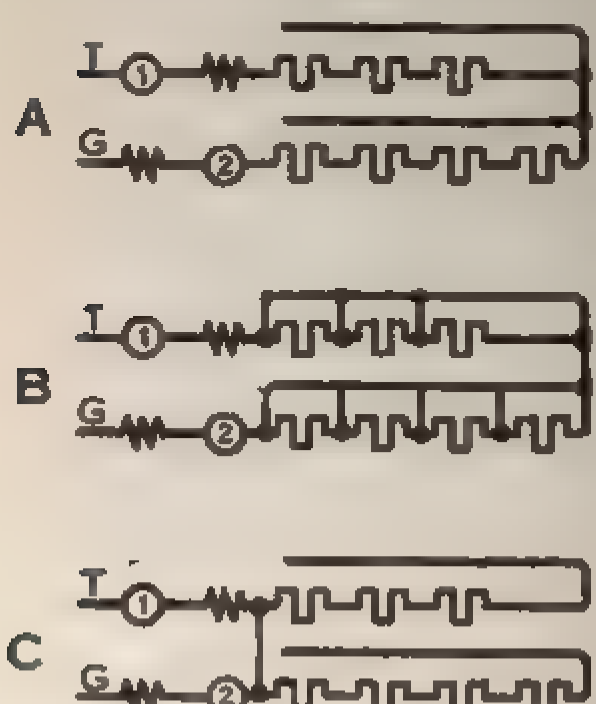


Fig. 1087 —Scheme of accelerating two motors in series.

One system used by the Westinghouse Company employs contactors which produce the same series-parallel connections as above, except that each contactor is operated by a piston moving in an air cylinder actuated by compressed air, carried in the reservoir under each car for the operation of the air brakes, at a pressure of about 70 pounds per square inch The admission of air to the cylinder is controlled by an electro-magnetic

valve, these valves being opened through control circuits from the 500-volt source of supply. The switches are opened by means of springs and are held closed by maintaining air under pressure on the piston in the air cylinder.

One of the later and most widely used types of control is the electro-pneumatic system developed by both the Westinghouse and the General Electric Companies. The complete control for a single car for multiple-unit operation in the General Electric P C. system contains in one box the line breaker, over-load relay, contactor elements for making the various motor and resistor connections, the reverser and the operating mechanism. The line-breaker elements, of which there are two, are electro-pneumatically operated contactors provided with powerful magnetic blow-outs. The power for operating these line breakers is obtained from the compressed air supply of the air brake system. Air is admitted through a small magnetic valve to a cylinder located underneath the operating mechanism This forces an air piston upward and closes the main contacts of the line-breaker elements against a powerful spring. The reverser, like the line breakers and main contactors, are built in the same way

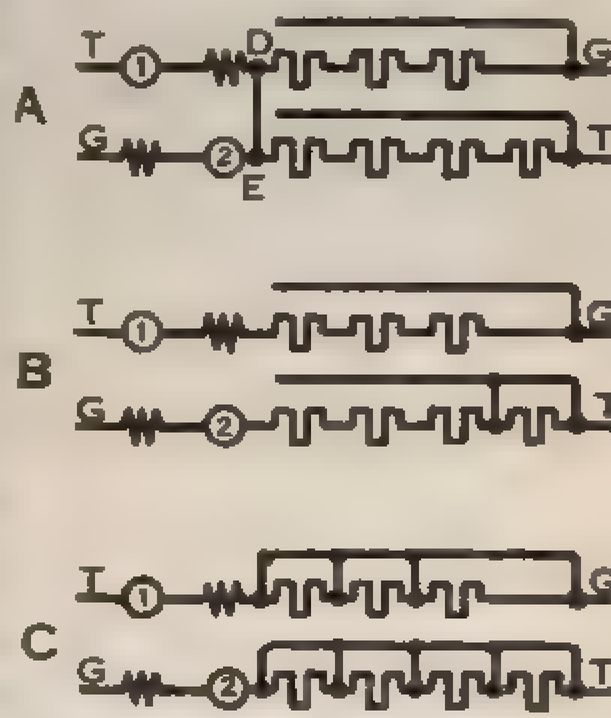


Fig. 1088 "Bridging" method of transition from series to parallel without opening the line circuit

The principal feature of this control system lies in the cam operated contactors which are provided with magnetic blow-outs. One of these is shown in Fig 1089. The movement of these contactors is effected by means of cams mounted on a rotating shaft which is located underneath the contactors and which bear upon the rollers of the contactor levers This shaft is rotated by a pinion and rack, the rack being actuated by the pistons of two air cylinders A front view of the controller is shown in Fig. 1090 and a rear view in Fig 1091 The air pressure against the piston of the "on" cylinder tends to rotate

the cam shaft to give full parallel connections of the motors, but if the air is admitted to the "off" cylinder it produces a rotation in the opposite direction. Each air cylinder has attached thereto

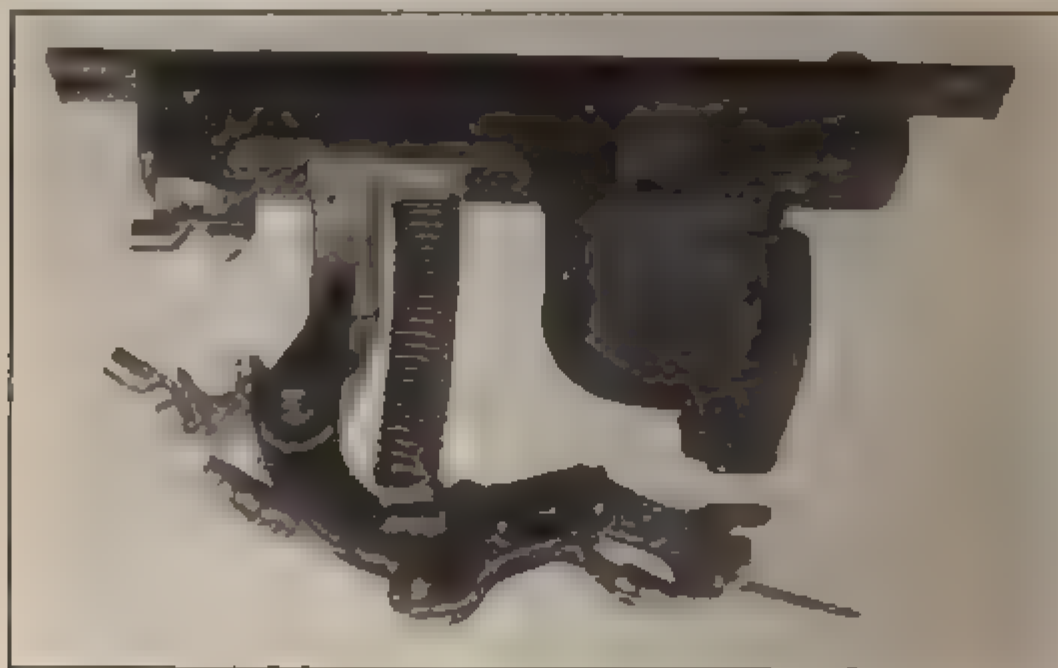


FIG. 1089.—General Electric, cam-operated contactor unit with electro-magnetic blow out for P. C. controller.

a magnetic valve which governs the admission of air to that cylinder. The magnetic valve attached to the "off" cylinder is so arranged that when the valve is in the normal or unenergized

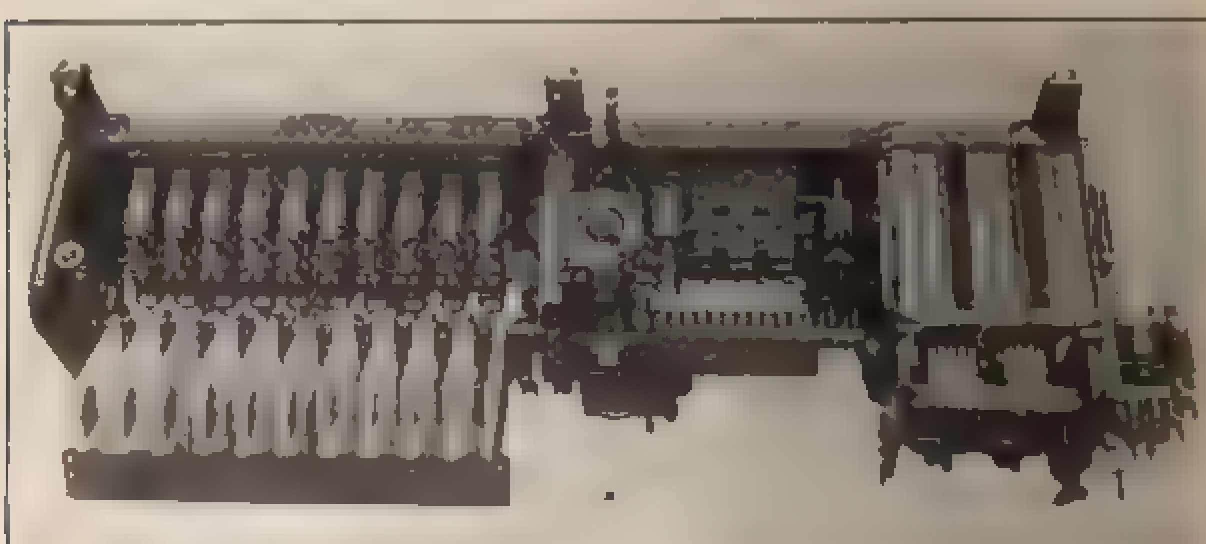


FIG. 1090.—General Electric. Type P. C. controller. Front view with arc-chute unit swung down.

position the "off" cylinder is charged with air from the supply reservoir, and when this valve is energized the cylinder is connected to the atmosphere. The magnet valve governing the "on" cylinder has the reversed function, that is, when in the

normal or de-energized position it connects the cylinder to the atmosphere, while in the energized position it admits air to the cylinder. It will thus be seen that, when neither of these magnets is energized, the air pressure will be against the piston of the "off" cylinder only, which will turn the cam shaft to the "off" position. In order to advance the cam shaft through the successive steps of the control, it is necessary to first energize the "on" magnet and to admit air to the "on" cylinder. This equalizes the pressure in both cylinders and the advancement of

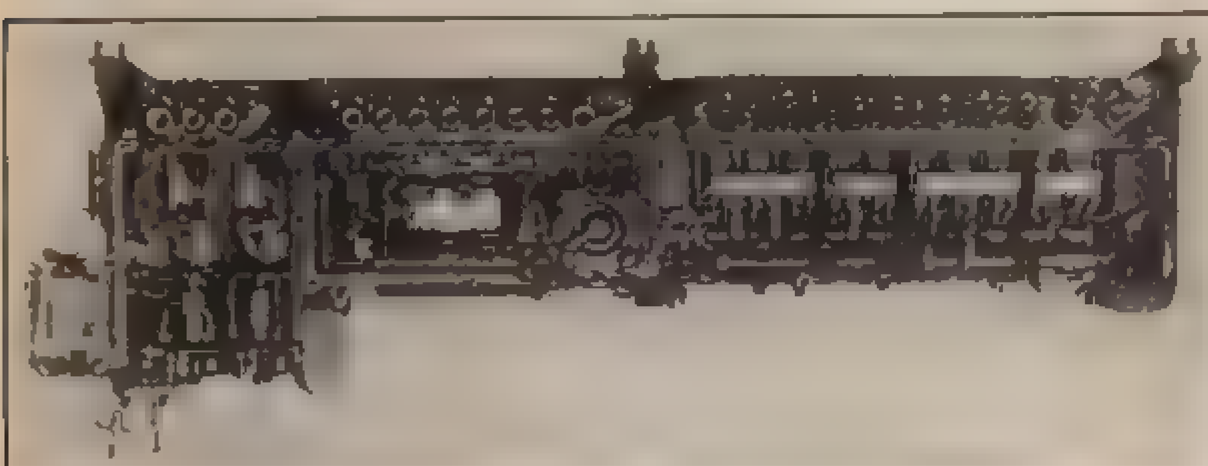


FIG. 1091.—General Electric Type P. C. controller. Rear view with covers removed.

the cam shaft is then obtained by reducing the air pressure in the "off" cylinder. As this reduction is governed by the magnet valve, it follows that the entire control of the cam shaft from the first series to the last parallel position of the motors is obtained by the energizing or de-energizing of a single valve. The advantage of this system of control is the elimination of all of the electric interlocks required on the electro-magnetic contactors. The operation of the contactors in a definite sequence, assured by their being mechanically operated, greatly improves the construction and makes it more simple.

SECTION XX CHAPTER IV

ELECTRIC RAILWAYS

MULTIPLE UNIT SYSTEMS

1. Explain in detail the plan of the Sprague General Electric multiple-unit system of control for railway units.

2. Wherein did the original Westinghouse system of multiple unit control differ from the General Electric?

3. What is the general plan of the latest type of electro-pneumatic system employed by both the General Electric and the Westinghouse companies?

ELECTRIC RAILWAYS

THE SINGLE-PHASE SYSTEM

The success of the single-phase railway system is due to the development of the compensated, series-connected, commutating type of motor devised by B. G. Lamme in 1902. An ordinary direct-current series motor would operate on alternating current provided the reverse impulses followed each other very slowly.

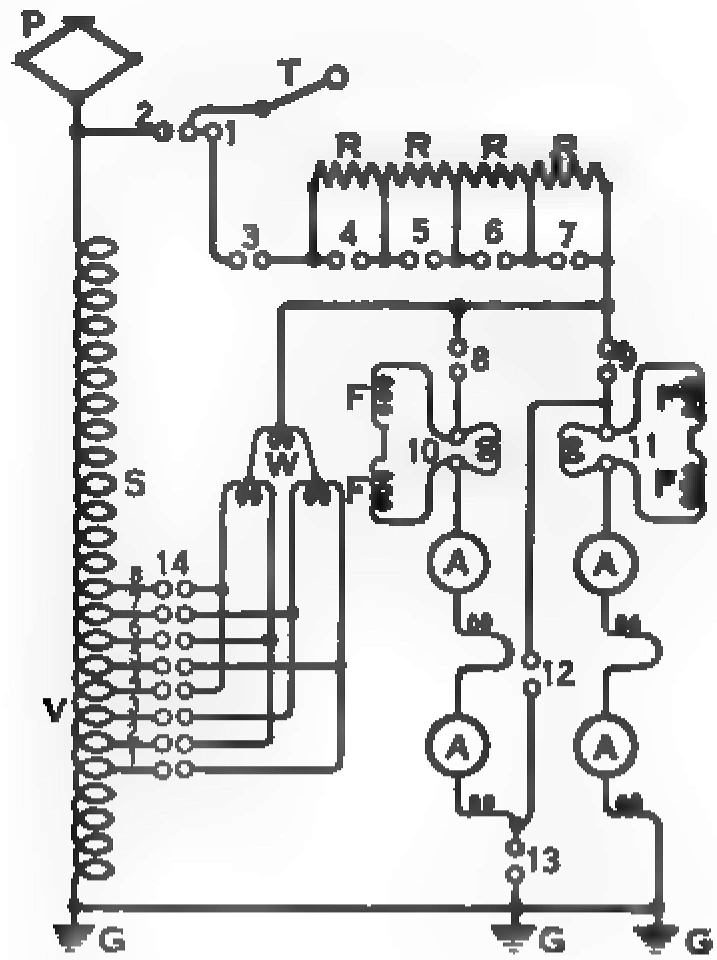


FIG. 1092.—Power circuits for four-motor equipment designed to operate on either A. C. or D. C. supply.

At commercial frequencies, however, the alternating flux would induce eddy currents in the field cores, hence for operation on such circuits the field structure must be laminated as thoroughly as the armature Furthermore, the self-induction of an ordinary field coil would involve a prohibitive drop in the alternating e.m.f Hence they must be more liberally designed, and sections of the field winding, instead of being connected in series as

on direct-current motors, must be connected in parallel. The self-induction of the motor as a whole is objectionable The self-induction of the field cannot be counteracted, but the self-induction of the armature can be overcome. This is accom-

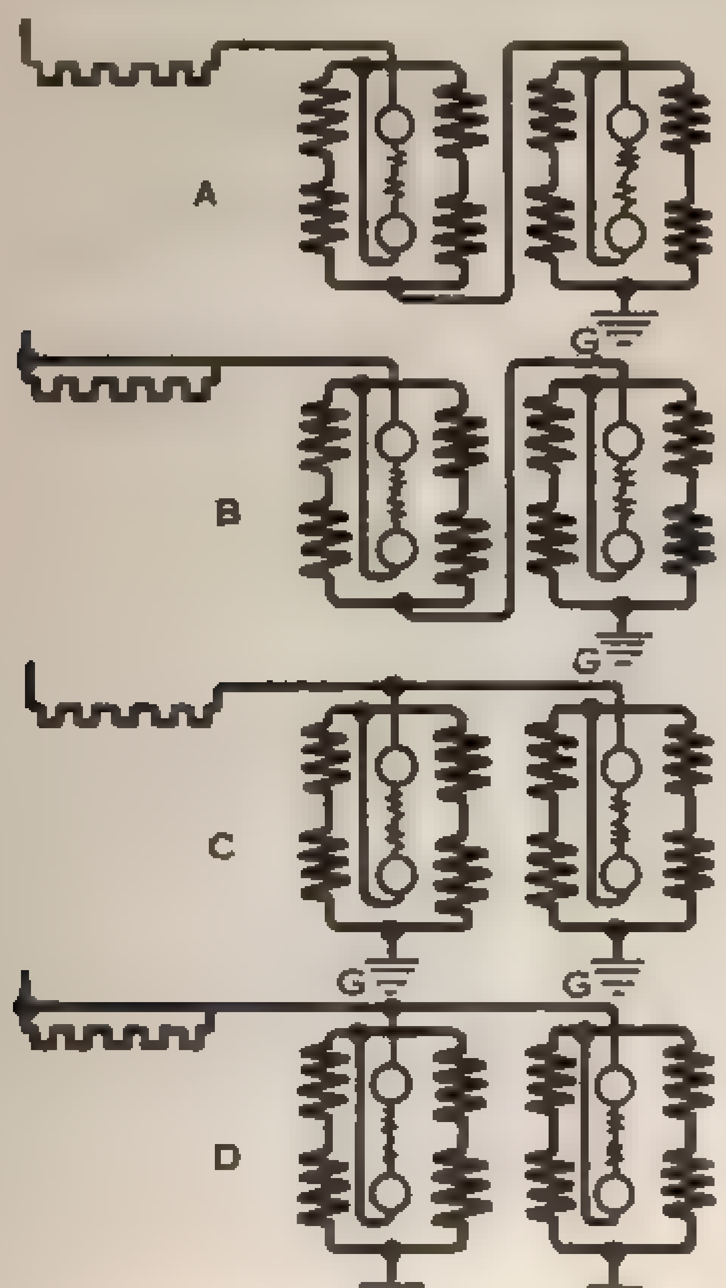


FIG 1093. Series and parallel connections of power circuit of four-motor equipment on A. C. supply.

plished by employing a compensating winding This is a stationary winding placed in slots in the field poles and connected so as to develop a magneto-motive-force equal and opposite to that produced by the armature. This produces in effect an anti-inductive winding which completely neutralizes the self-induction of the armature winding and greatly improves the

power factor and performance of the motor. Another difficulty which had to be overcome was the sparking at the brushes during commutation, due to the fact that each coil on the armature, while it was short-circuited by the brush, was subjected to an

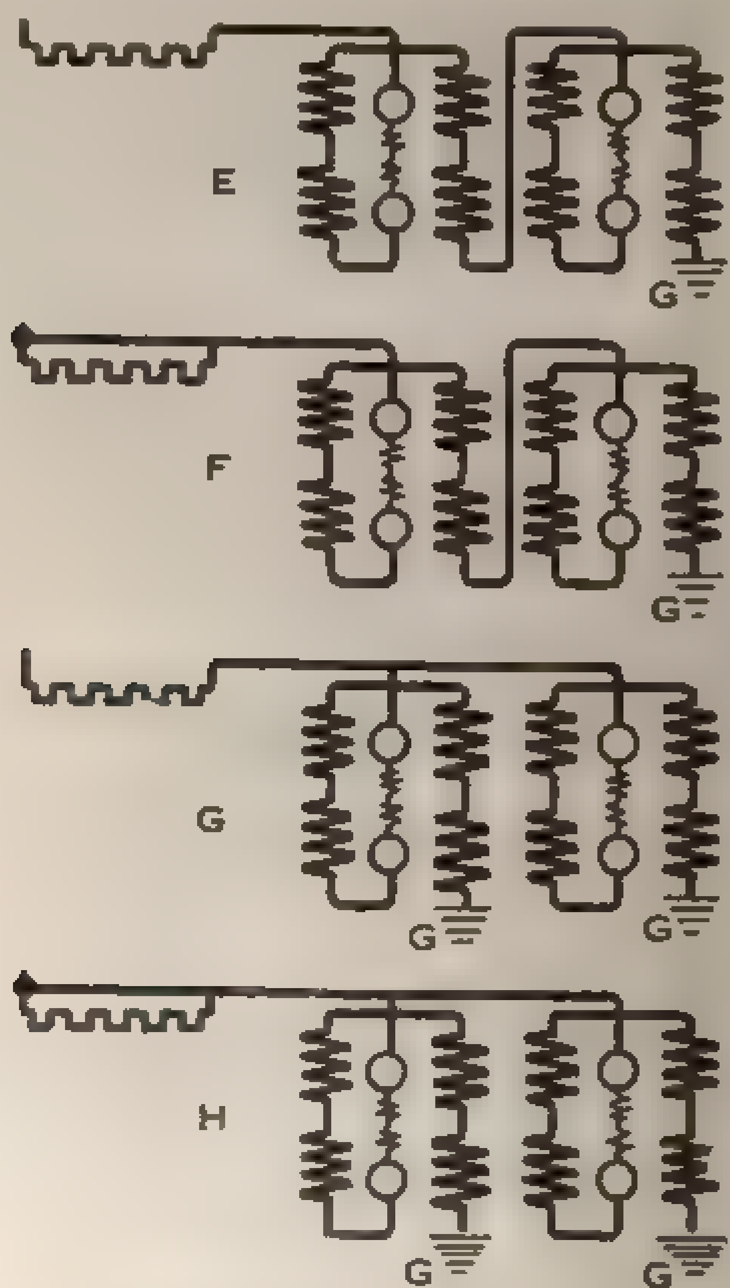


FIG. 1094.—Series and parallel connections of power circuit of four-motor equipment shown in Fig. 1093 when arranged to operate on D.C. supply.

alternating magnetic flux. There was thus a transformer action with a resulting current which was interrupted when the coil passed out from under short circuit. To overcome this, high-resistance leads were connected between the winding and the commutator segments. These leads were not in circuit with the series of coils between adjacent brushes, but only in circuit

between the terminals of the series and the segments from which current was collected. By reducing the number of convolutions in a coil to the minimum, and by introducing high resistance leads in the path of the short-circuited coil, the value of this current in the short-circuited coil was reduced so low that sparking was effectively overcome This is the design of practically all of the series motors used on the single-phase railway electrifications at the present time.

The general plan of this system is as follows: The power is generated by three-phase alternators, and is transmitted at from

Fig. 1095 —Latest type of Westinghouse Baldwin A. C. locomotive, used on New York, New Haven & Hartford Railroad.

11,000 to 66,000 volts to substations along the railroad where it is reduced by static transformers to 11,000 volts It is delivered at this pressure, single phase to the trolley wire, and is collected by pantograph trolleys and led to a transformer on the locomotive. Here it is reduced to 550 volts, which is divided between two motors connected permanently in series and wound for 275 volts each. The frequency is 25 cycles Control of speed is effected in small equipments by varying the voltage on the motors by means of induction regulators On large equipments

taps are taken from different sections of the transformer secondary, and electro-magnetic contactors are employed, by which the connections are made to different taps to produce the desired acceleration. The same equipment is designed for use on direct current with resistors and series-parallel connections. A diagram of connections for combined A.C. and D.C. operations is shown in Fig. 1092. Combinations of series and parallel connections are shown in Figs. 1093 and 1094 for A.C. and D.C. respectively. In passing from one tap to another in a transformer either the intermediate sections would be short circuited or the circuit broken, were it not for a **preventive** coil. This consists of a small reactance *W*, Fig. 1092, on a closed magnetic circuit, the ends of the winding being connected to the adjacent transformer taps while the middle point leads out to the motors. No impedance is encountered by currents passing simultaneously from the two taps to the middle point on its way to the motor, but any current which tends to circulate between the two taps and through the preventive coil encounters the self-induction thereof and is thereby limited to a low value.

The New York, New Haven and Hartford Railroad system is the most noteworthy example of single-phase operation. One of the latest types of locomotive on this system is shown in Fig. 1095.

SECTION XX CHAPTER V

ELECTRIC RAILWAYS

THE SINGLE-PHASE SYSTEM

1. Explain the advantages and disadvantages of the single-phase railway system.

2. (*a*) Can the motors used on the single-phase system be operated on both D. C. and A. C.?
   (*b*) How is this made possible?
   (*c*) What are the relative voltages impressed on the motors in the two cases?

3. (*a*) What kind of control is used when running on A. C.?
   (*b*) What kind of control is used when running on D. C.?

4. Explain the use of the "preventive coil" used with A. C. control.

5. What is the trolley voltage customarily employed on the single-phase system? What determines the selection of this voltage?

ELECTRIC RAILWAYS

HIGH-VOLTAGE D. C. SYSTEMS

The high-voltage direct-current system is the natural outgrowth of 600-volt operation. For many years it was thought impracticable to insulate apparatus or to design it for successful commutation above 600 volts. The introduction of the interpole or commutating pole motor so corrected the commutation difficulties that it was found possible to design motors for considerably higher pressures. The first attempt in this direction was a 1,200-volt system. To operate at this pressure, cars were provided with a four-motor equipment. Each motor was wound for 600 volts but insulated for 1,200 volts. Two motors were then permanently connected in series and the two sets handled in the various series-parallel combinations in the usual way. Current for operating the contactors to produce the various series-parallel combinations, the air-compressor and the lighting circuits was obtained from a dynamotor wound for 1,200 volts, provided with two commutators connected in series and arranged for supplying the control circuits from the middle point at 600 volts.

The first method of supplying 1,200 volts to the trolley was by connecting two 600-volt rotary converters in series and insulating them from the ground. The results were so satisfactory that many installations were immediately undertaken. Some of these were at 1,500 volts. Fig. 1096 shows the arrangement of the dynamotor on such a circuit, while the various combinations of the motors, fields and resistors is shown in Fig. 1097. Following the use of the dynamotor for the operation of lights, a more satisfactory plan was found to be the employment of a motor-generator, in which the generator was of the third-brush type which insured a steady voltage under wide changes of speed of the generator set due to changes in trolley voltage. After the 1,200-volt system was perfected, 2,400 volts was attempted. It will be remembered that the economy of a transmission varies as the square of the potential employed. It will be evident that if substations were required 10 miles apart for the successful

operation of a 600-volt system, increasing the trolley pressure to 1,200 volts would produce the same results with substations 40 miles apart; and with 2,400 volts the substations could be placed 160 miles apart.

The first installation at 2,400 volts was the electrification of the Butte, Anaconda and Pacific Railway. This involved 75 miles of track and 17 locomotives composed of two 80-ton units each, operated in multiple-unit combinations capable of hauling a

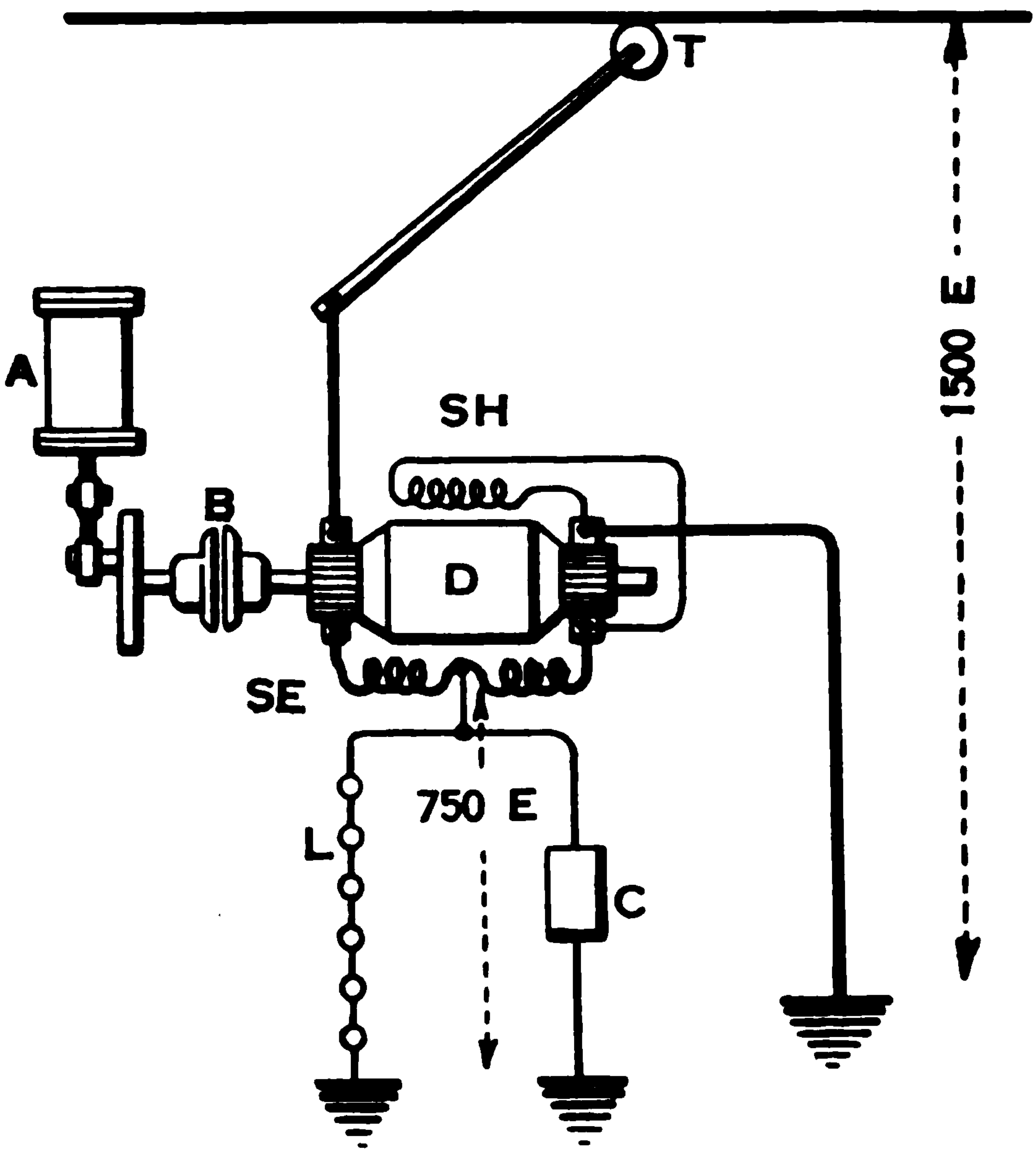


FIG. 1096.—Dynamotor for supplying 750 volts for lighting and control circuits from 1,500-volt trolley.

3,400-ton freight train 21 miles per hour on a level. These locomotives carry four 260-horse-power motors in each section, or eight in all, giving 2,100 horse power. Each motor takes 190 amperes and is wound for 1,200 volts, but insulated for 2,400 volts. They are connected permanently two in series. Type M control, giving 19 points, 10 series, and 9 multiple notches, is employed.

A late and noteworthy installation of high voltage D.C. installation is that of the Chicago, Milwaukee and St. Paul Railroad. This was a General Electric installation originally, employing

3,000 volts on the trolley. The first locomotives were equipped with 400-horse-power type G. E. 253-*A* motors wound for 1,500 volts, insulated for 3,000 volts and connected permanently, two in series. These locomotives were built in two sections and carried in all eight motors totaling 3,200 horse power. These motors weighed 14,860 pounds each. The total weight of the locomotive was 384 tons.

Power is developed in three-phase generating stations, where it is raised to 100,000 volts and transmitted to substations located along the line, where it is reduced by static transformers to 2,300 volts and then supplied to synchronous motor-generator sets. Each of these sets consists of one 2,300-volt synchronous

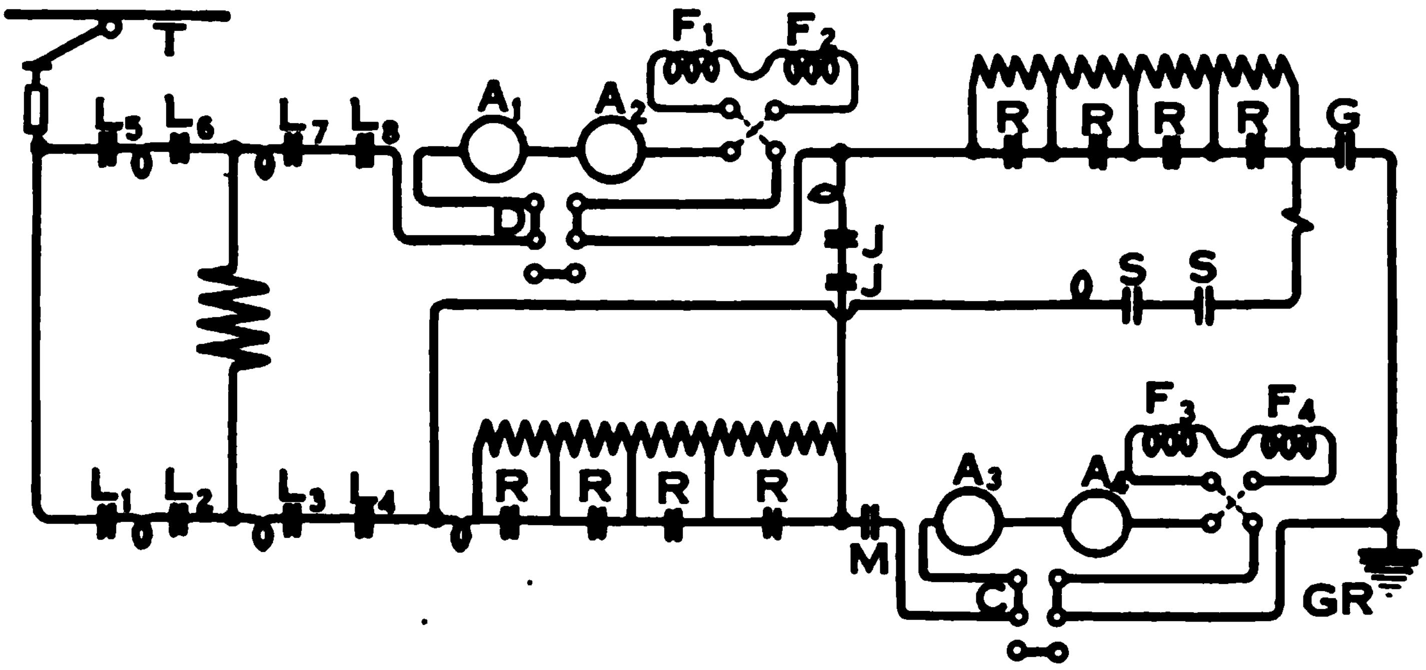


FIG. 1097.—Power circuit for four-motor equipment designed for operation on 1,500-volt trolley.

motor direct-connected to two D. C. generators of 1,500 volts each connected in series. On the same shafts are mounted two direct-connected exciters which supply current for the fields of the two main generators and the synchronous motor.

The later Westinghouse-Baldwin locomotives for the Chicago, Milwaukee and St. Paul Railroad are shown in Fig. 1098. They are 88 feet long over all and have an equipment of 4,200 horse power. There are six driving motors of the twin-armature type as shown in Fig. 1070, both armatures being mounted in a single frame. Peripheral speed is a limiting feature in such a railway motor design. With two small motors it is possible to use a speed twice that possible with one large motor. Each motor has one-half the number of poles of practically the same size as would be required by one equivalently large motor. Therefore two of

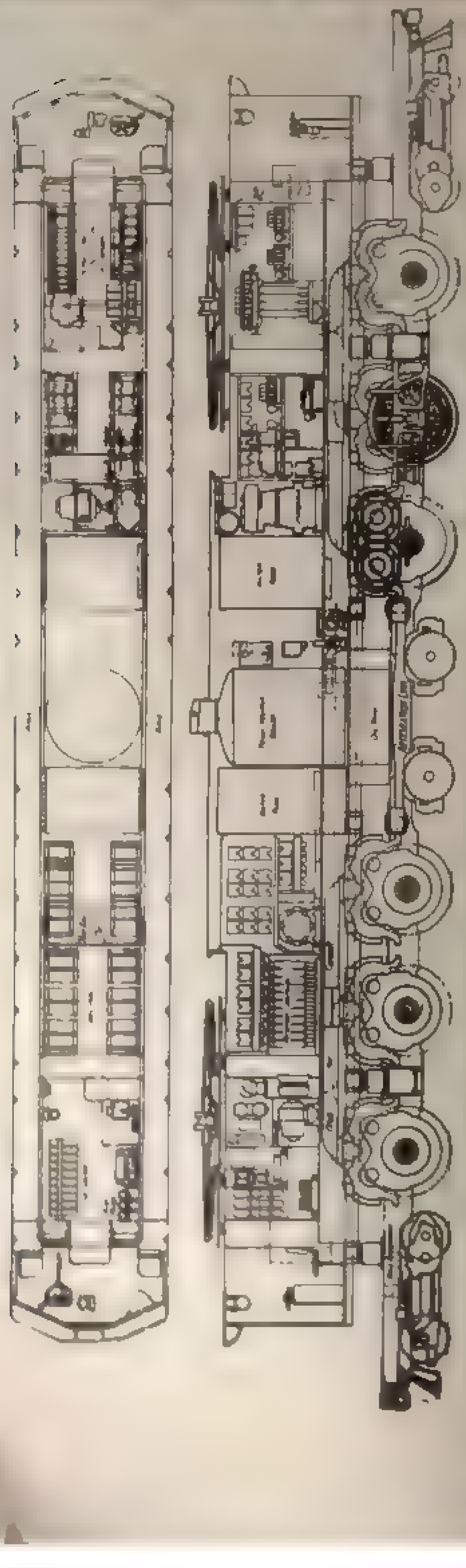


FIG. 1098.—Plan and sectional view of Westinghouse-Baldwin direct-current locomotive for C., M. & St. P. Railroad. Twelve motors are employed to drive six axles, trolley pressure 3,000 volts; length between couplers 88 feet 7 inches.

the small motors have practically the same number of parts, such as field coils, armature coils and brush holders, as would be required by one large motor. As one small motor has a diameter practically half that of one equivalently large motor, a saving in space and weight results. Finally, twelve of the small motors actually cost less than would six larger motors having the same aggregate output.

The fields are of the standard four-pole type with four main poles and four interpoles for each armature. Each armature is wound for 750 volts and the two armatures and the two sets of field windings are connected permanently in series so that the rating of the complete motor is 1,500 volts. The motor is designed for field control by means of inductive shunts. The one-hour rating is 700 horse power. The motors are mounted rigidly on the cross bars of the running gears, one directly above each driving axle. Each motor is geared to a quill centered in bearings in the motor frame and surrounding the driving axle with a clearance of 1¾ inches all around. The quill is connected to the driving wheel by long helical springs.

The six motors are arranged to be connected in three combinations: First, all in series, giving one-third speed; second, three in series, two in parallel, giving two-thirds speed; third, two in series, three in parallel, giving full speed. Inductive shunts are applied to the fields on all three of these positions. Shunt transition is used in passing from one combination to the next.

The latest General Electric locomotives for the same railroad weigh 521,000 pounds and are 76 feet long (see Fig. 1099). They are equipped with twelve bipolar gearless motors of similar design to those originally used on the New York Central electrification.

Each motor is designed for 1,000 volts and develops 266 horse power. This type of motor gives very high efficiency in average operation as there are no journal bearings or gears. The pole pieces and field poles are fastened to cross transoms of the truck, and the magnetic flux passes horizontally in series through all twelve motors, finally returning through the locomotive frame. The arrangement may be clearly seen from the sectional view in Fig. 1100.

The articulation joints between the trucks are made in such a manner that large surfaces are in contact to provide an easy path for the flux. The pole pieces are made flat in order to prevent

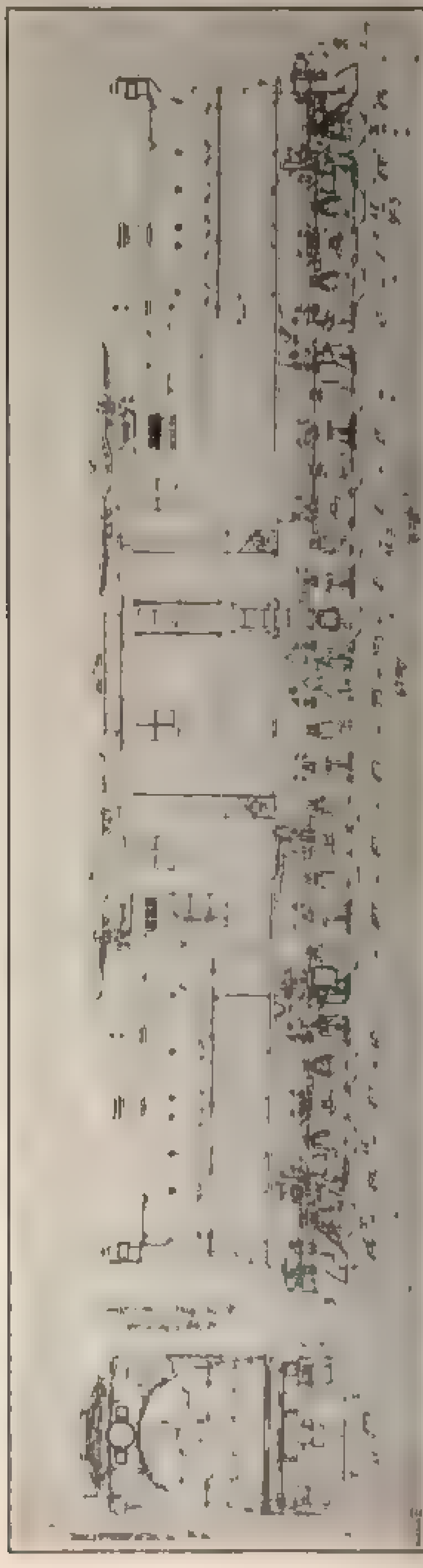


FIG. 1099.—Plan view of General-Electric direct-current locomotive for C., M. & St. P. Railroad. Twelve gearless motors drive twelve axles, trolley pressure 3,000 volts; length between couplers 76 feet.

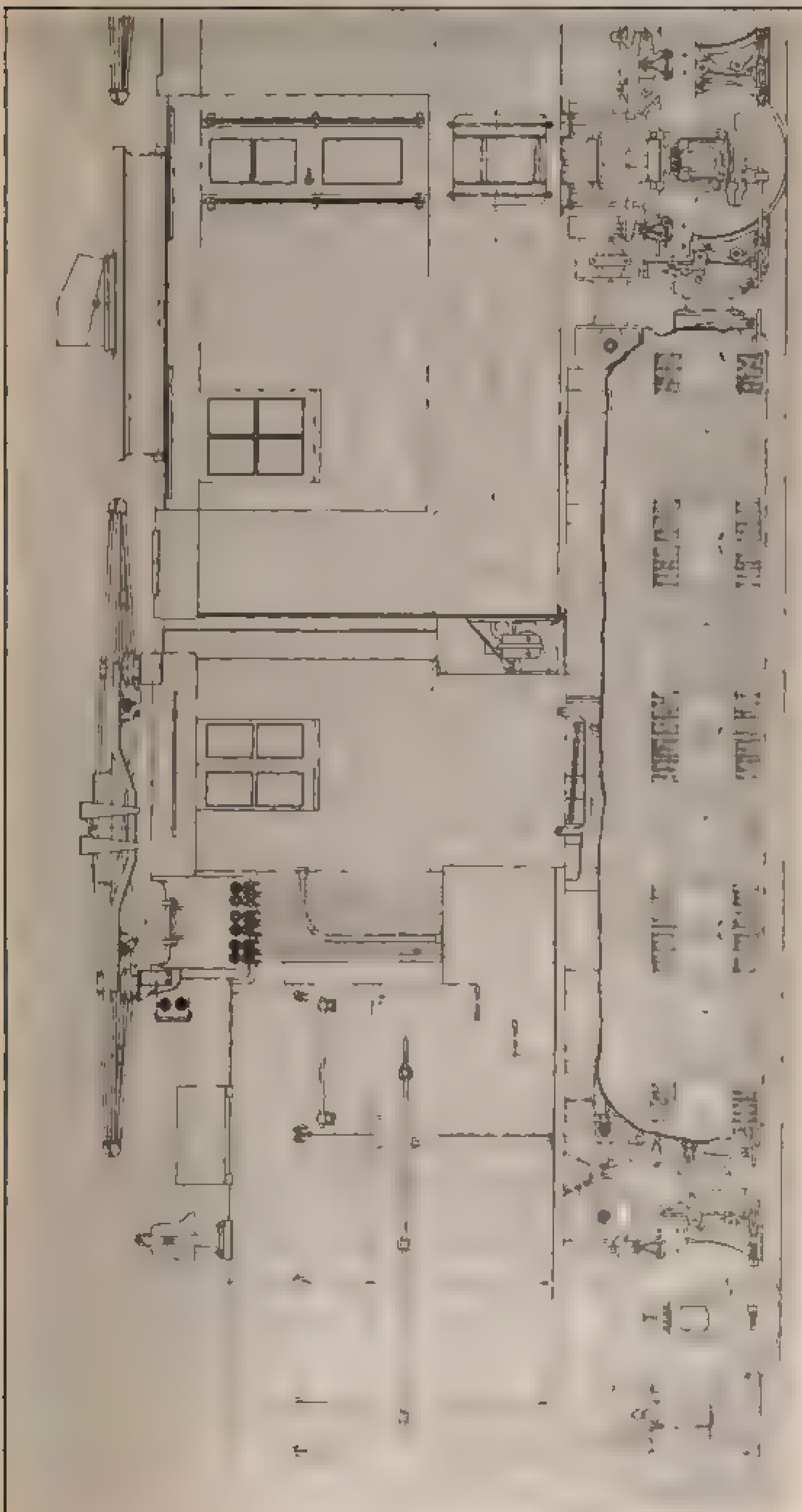


FIG 1100 —Sectional view of General-Electric locomotive for C., M. & St P. Railroad, showing construction of gearless motors.

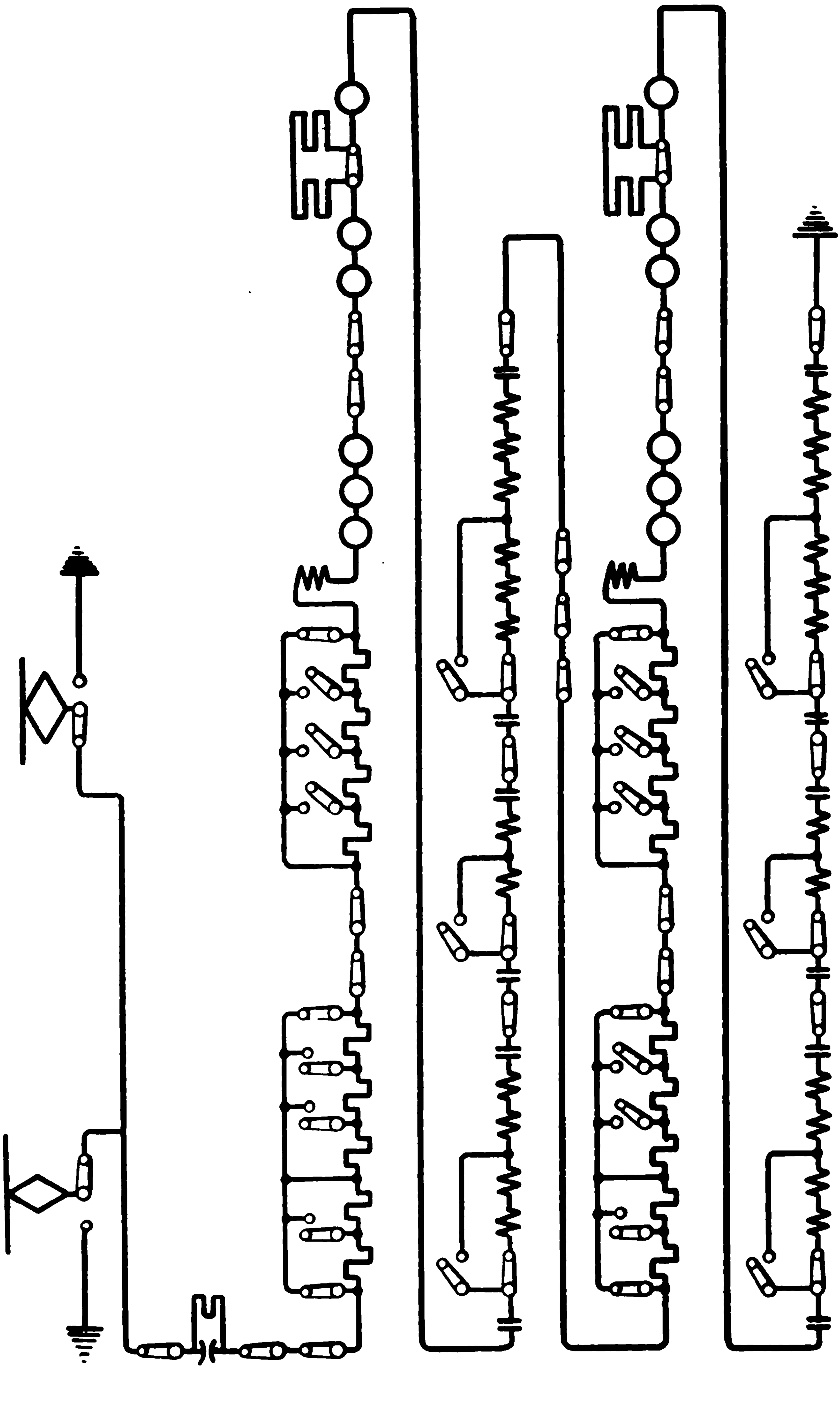


FIG. 1101.—Power circuits of General Electric direct-current locomotives on C., M. & St. P. Railroad, showing first running position.

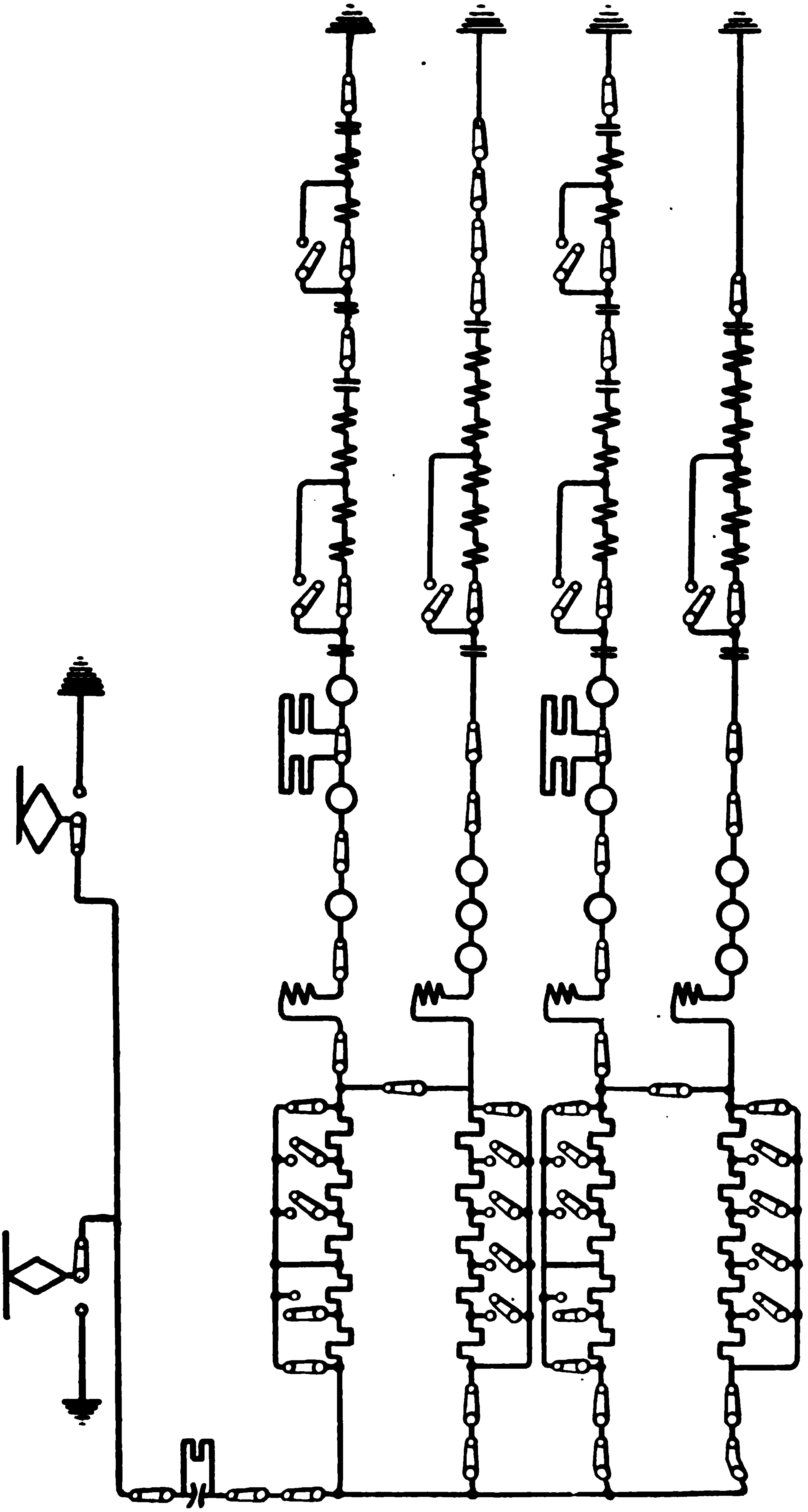


FIG. 1102.—Connections of motors on C., M. & St. P. Railroad for last running position, giving highest speed.

them from coming in contact with the armature during the vertical movement of the truck frame on its springs or when removing or assembling the armatures. A minimum clearance of one-eighth inch is allowed between the armatures and pole pieces.

The control is arranged for four motor combinations:

The first combination has nine rheostatic steps, one full field step and one tapped field step with the motors in series across 3,000 volts.

The second combination has six rheostatic steps, one full field step and one tapped field step with six motors in series and two sets in multiple.

The third combination has eight rheostatic steps, one full field step and one tapped field step with four motors in series and three sets in multiple.

The fourth combination has eight rheostatic steps, one full field step, one tapped field step with three motors in series and four sets in multiple.

This results in a total of 39 control steps, with a choice of eight operating speeds exclusive of resistance steps. The first running position is shown in Fig. 1101, and the last running position in Fig. 1102.

The 5,000-Volt D. C. System of Railway Control

An experimental system operating successfully between Jackson and Grass Lake, Michigan, with a trolley voltage of between 5,000 and 7,000 volts, has been successfully installed. The car designed for this purpose is enabled to operate over the 600-volt line within the city limits and by means of suitable switching mechanism, upon the 5,000-volt trolley in the suburbs.

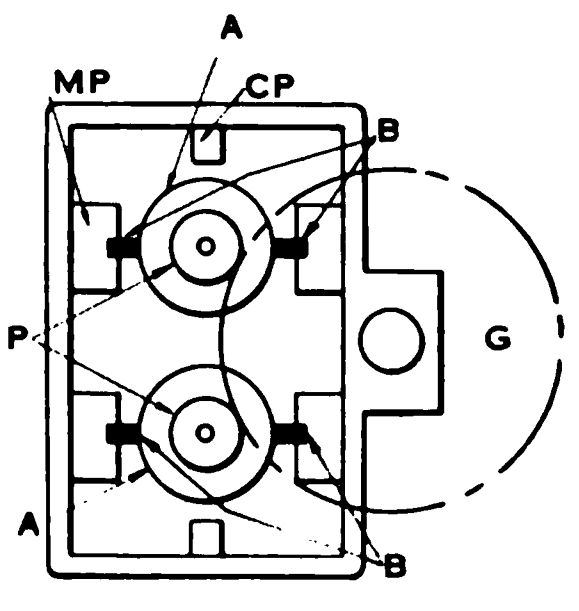


FIG. 1103.—Plan of Westinghouse twin-armature, 5,000-volt, direct-current railway motor.

Because of the small current required at this voltage, it was found possible to employ a mercury arc rectifier to rectify the A. C. supply without the use of a rotary converter. The motor was, of course, the most difficult part of the system to design.

It is of the twin-armature, bipolar type shown in Fig. 1103. The bipolar motor permits the use of double the voltage on a commutator that is possible with a four-pole motor of the same commutator diameter because of the greater space between brushes. The twin-armature type weighs little more than a four-pole single-armature motor of the same horse power. Fewer coils are required than with a four-pole motor. The two armatures are geared to the same axle and act as one unit. The pressure of the gears is thus divided in half. The two armatures are wound for 1,250 volts each and connected permanently in series, thus enabling each motor to receive 2,500 volts. The

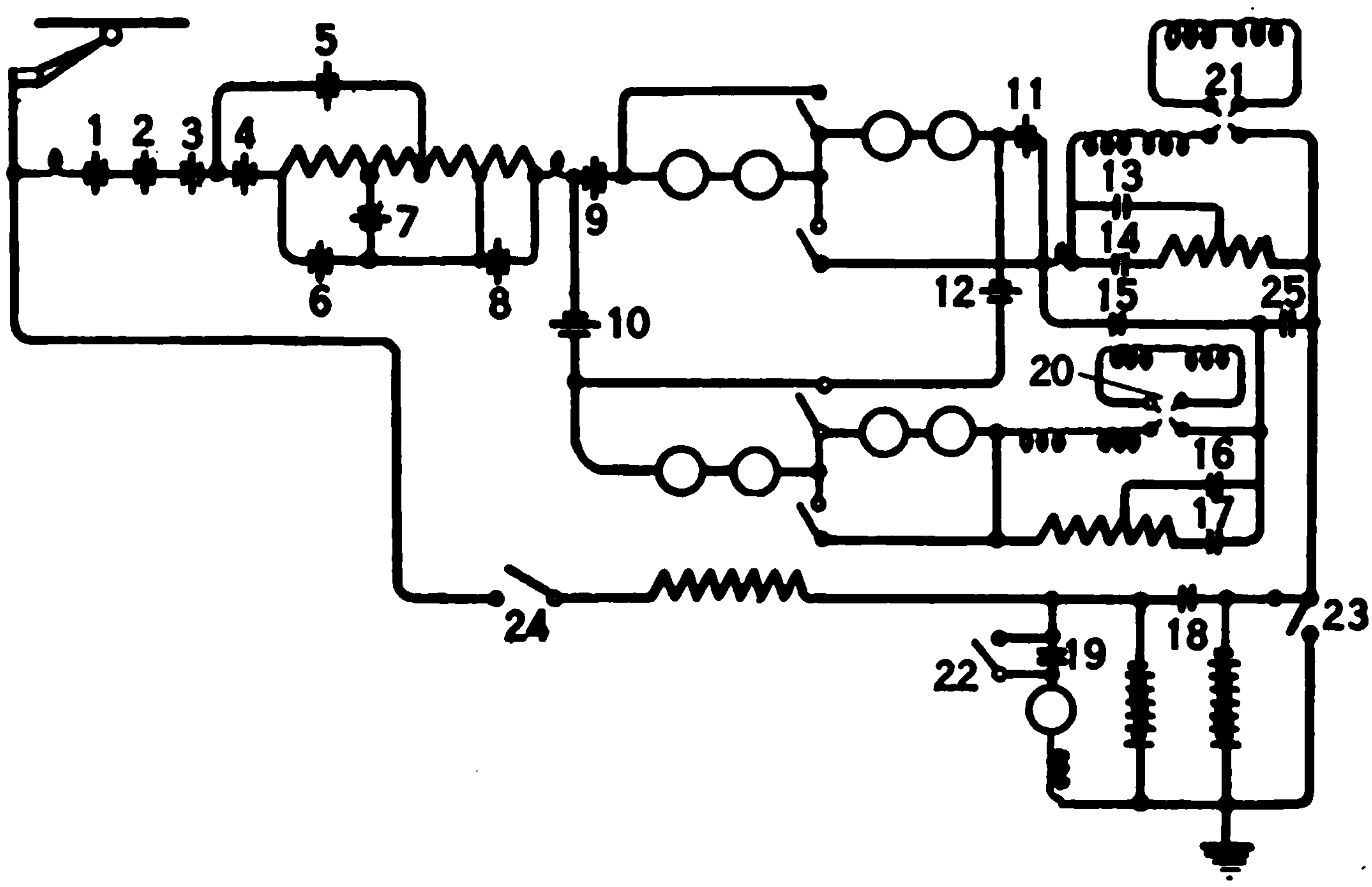


FIG. 1104.—Scheme of control for Westinghouse 5,000-volt, direct-current railway system, also capable of operation on 600 volts.

40-ton experimental car employed involved an equipment of four motors, each being rated at 100 horse power. Because of the high voltage, each motor required only 16 amperes. The power circuit is shown in Fig. 1104. When operating in the city limits at 600 volts the proper speed is obtained by shunting the motor fields and placing all four machines in parallel. The control circuit is always operated from a 150-volt storage battery placed in series with the circuit for operating the propelling motors on the ground side. All of the auxiliaries are operated from this battery. The source of power is a three-phase 60-cycle system which feeds through the mercury rectifiers to the D. C. trolley so that the three phases are equally loaded.

SECTION XX CHAPTER VI

ELECTRIC RAILWAYS

HIGH-VOLTAGE D. C. SYSTEMS

1. Explain the initial steps in the development of the 1,200-volt D. C. railway system.
2. Explain the general plan of the 2,400-volt D. C. railway system.
3. How is the current for operation of lighting and control circuits obtained on systems employing direct current at a pressure of 1,200 volts and upwards on the trolley?
4. Explain the general plan of the C. M. & St. P. electrification.
5. Describe the construction of the Westinghouse locomotive for the C. M. & St. P. system, including the scheme of control.
6. Describe the construction of the General Electric locomotive for the C. M. & St. P. system, including the scheme of control.
7. Explain the details of the Westinghouse experimental 5,000-volt D. C. electrification at Jackson, Michigan.

ELECTRIC RAILWAYS

ELECTRIC BRAKES

Dynamic Braking.—All electric cars having an equipment of either two or four motors may be stopped by means of dynamic braking, without the aid of mechanical brakes or current from the trolley. This plan consists in converting one of the machines into a generator while the other becomes a motor connected for reverse operation, and the reaction of the current in both machines is such as to retard the car. On a level it would be brought to a rest. On a grade it would be retarded to a very slow speed but would not be held absolutely stationary as the reaction of the induced currents only exists while the car is in motion,

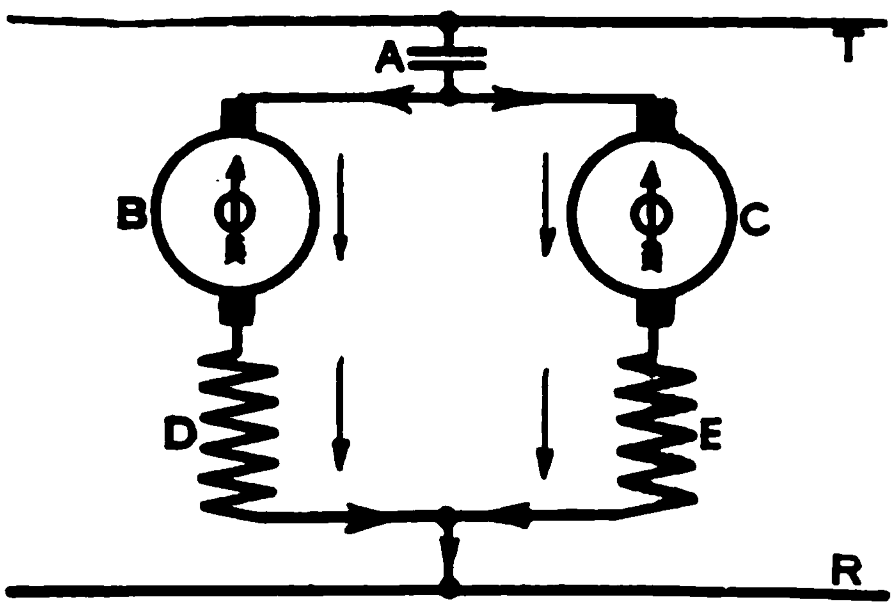


FIG. 1105.

hence the car would creep slowly to the bottom of the grade. The action may be understood from a consideration of Fig. 1105. Here the current from the trolley wire *I* divides between motors *B-D* and *C-E*, passing through them to the rail *R*. The counter e.m.f. set up by these motors is shown by the feathered arrows in the center of the armature.

Now if a shunt motor is allowed to rise in speed until its counter e.m.f. exceeds the impressed, it will send current through its field in the same direction as the current from the line as shown in Fig. 1106. Here current passes from line *L* down through armature and down through field as shown by the arrows, the counter e.m.f. being in the direction of the feathered

arrow. If, however, the counter e.m.f. exceeds the line voltage so that the armature furnishes current in the direction of the feathered arrow, current will flow back into the line in the reverse direction to which it entered the armature and will flow to the right in the field in the same direction as before. As the current in the armature is thus reversed, the torque reverses and, instead of the machine being a motor tending to develop mechanical power, the reaction is that of a generator, which requires power to drive it.

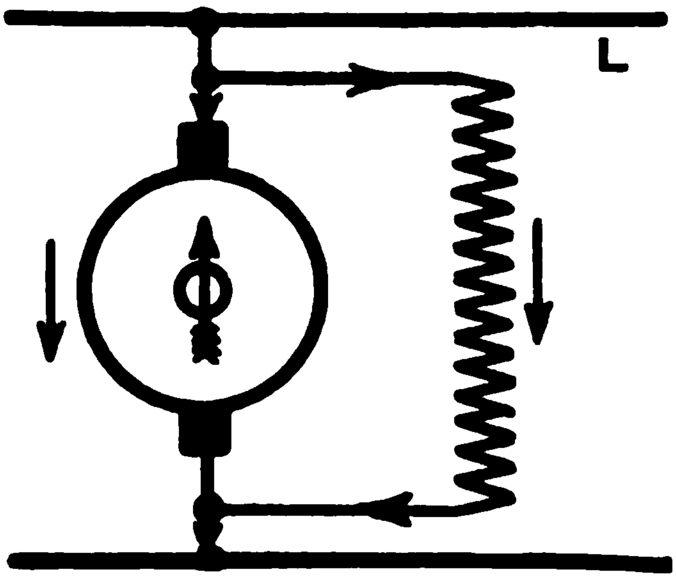


FIG. 1106.

Should the motors in Fig. 1105 rise to a speed where the counter e.m.f. equals that of the line, they could not furnish current back into the line, because at the moment when the counter e.m.f. equaled the impressed, the field current would be zero. In fact, such a condition sometimes results in a short circuit from trolley to rail which blows the circuit breakers at *A*. Furthermore, were the counter e.m.f. to actually succeed in producing a reverse

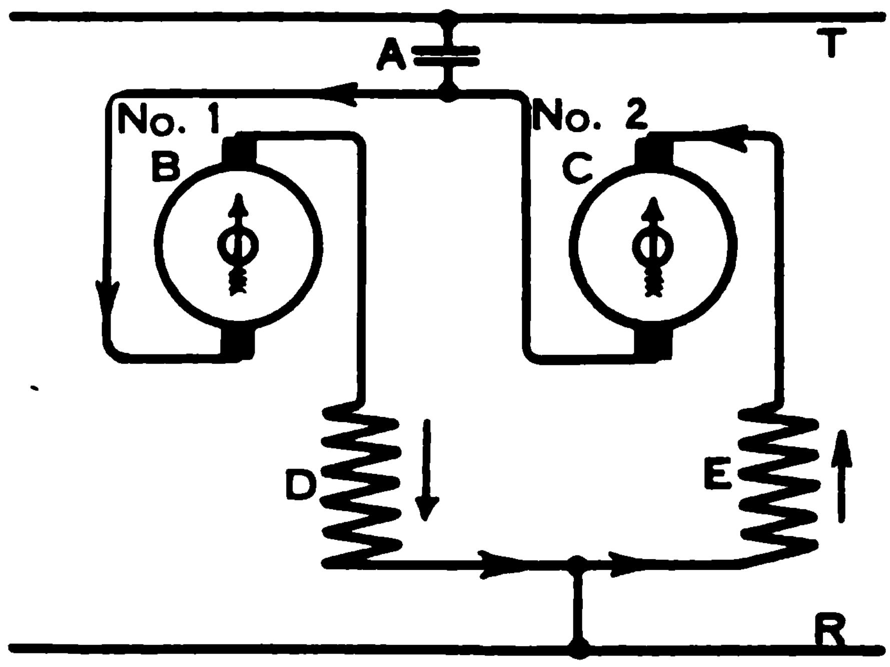


FIG. 1107.—Connections of motors in two-motor car equipment for dynamic braking.

current, it would tend to destroy the residual field magnetism which is in the direction produced by the initial current from the trolley as shown by the arrows pointing downward through *D* and *E*.

To produce dynamic braking it is first necessary to throw the

controller handle off. The circuit breaker at A should then be opened. The reversing switch should next be thrown and the controller opened to any parallel notch. The connections will then be as in Fig. 1107. The motors are then driven by the energy of the moving car. At the instant these connections are established the counter e.m.f. of the two will be in opposition and should theoretically be equal to each other. As a matter of fact, however, there are never two machines precisely alike. One has a little more residual magnetism than the other. Therefore its counter e.m.f. becomes a little greater than the other. The one with the higher e.m.f. becomes a generator. Let that be machine No. 1. This immediately becomes a source of electrical energy, furnishing current in the direction of its counter e.m.f., upward through B and downward through its field D, thereby building up in the same direction the residual magnetism established by the original trolley current, thence over and upward through E. It will be observed that the current is in the reverse direction in this field to what it was in E, Fig. 1105. The current then flows down through the armature C against its counter e.m.f. just as it did at C, Fig. 1105. Machine No. 2 then becomes a motor with the current in the armature in the same direction as before but with the current in the field in the reverse direction. This tends to drive this motor backwards, which is in opposition to the energy of the moving car. The current continues back to Machine No. 1, passing through the armature of this machine in the opposite direction to what it did in B, Fig. 1105, then through D in the same direction as before. The torque of this machine is therefore reversed. As the current in the two machines is the same, they react equally upon the driving energy supplied by the car, and the faster the car is moving the quicker it tends to stop. This action, being severe, subjects the car equipment to great strain and may strip the gears. Therefore it is used only in case of emergency.

The Westinghouse Electric Traction Brakes.—There have been a variety of electrical brakes devised for electric cars. Most of these have been discarded in favor of air brakes, which are considerably simpler and more reliable. One of the most widely used electric brakes still employed to a considerable extent is that designed by the Westinghouse Company, shown in Fig.

1108 This is a traction brake employed between the two pairs of wheels of a truck and is drawn to the rails by the action of an electro-magnet operated from the car, at the same time increasing the pressure of the wheel brakes on the wheels. The electro-magnet, *A*, dividing the track shoes *BB* into two parts, is secured by links to the two push rods, *C* and *J*, and supported at a proper distance above the rails by the adjustable springs *H-H*. The push rods are attached to the lower ends of the brake levers *D*, which are connected at their upper ends by the adjustable coupling *G* and are pivoted at an intermediate point to the brake shoe holders *E*, carrying the wheel brake shoes and the supporting rods *F*, suspended from the truck frame. The push rods *C* and *J* are telescopic, so that a movement of the track shoes

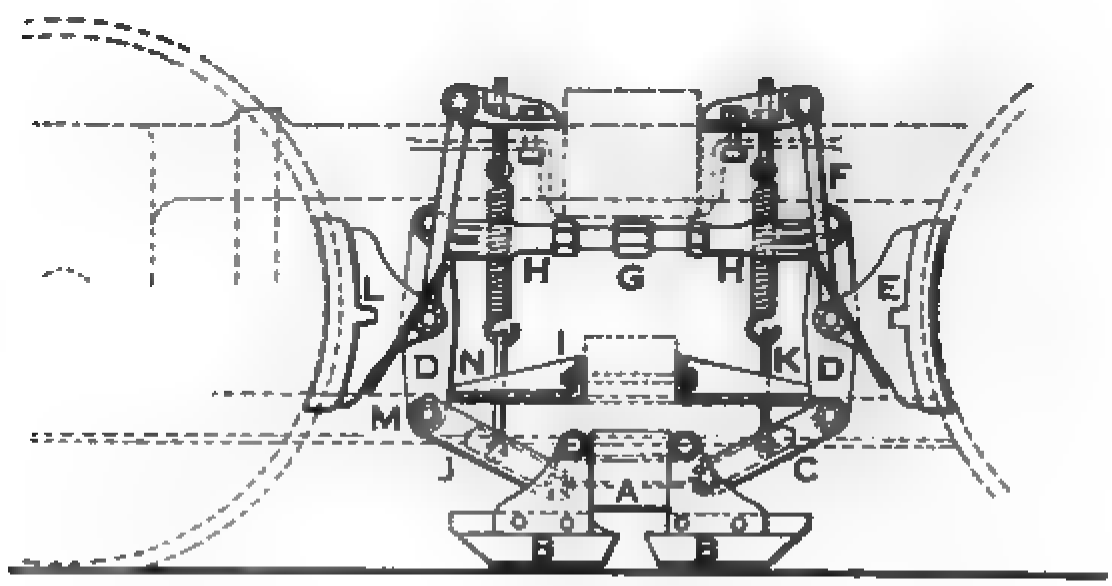


FIG. 1108.—Plan of Westinghouse electric track brake.

toward the right, as when the car is progressing to the left, causes the wheel brake shoe *E* at the right to be applied to the wheel and the connection *G* to move to the left, thereby applying the wheel brake shoe *L* at the left. The stop, *N*, prevents the lower end of the brake lever at the left from following the track brake shoe to the right. A relative movement of the track brake shoe to the left is obviously accompanied by the application of the left brake shoe through a corresponding movement of the parts in reverse order

The device controlling the brake is incorporated in the controller which operates the car, and is operated either by the same control handle or, in some instances, by a separate one. The motors have their armature connections reversed as for dynamic

braking as shown in Fig. 1109, except that here they are placed in parallel and the connections are such as to supplement the fields through the counter e.m.f. developed. The current passes upward through the two armatures A and A', thence downward through the fields F-F', then through an adjustable current limiting resistance R and through the brake coils B' and B and thence back to the motors which are operating in the capacity of generators. It will thus be seen that the stopping of the car is due to the combined action of the motors in functioning as generators, the application of a powerful track brake operating on a relatively large surface of the track, and the simultaneous application of wheel brakes mechanically applied through the

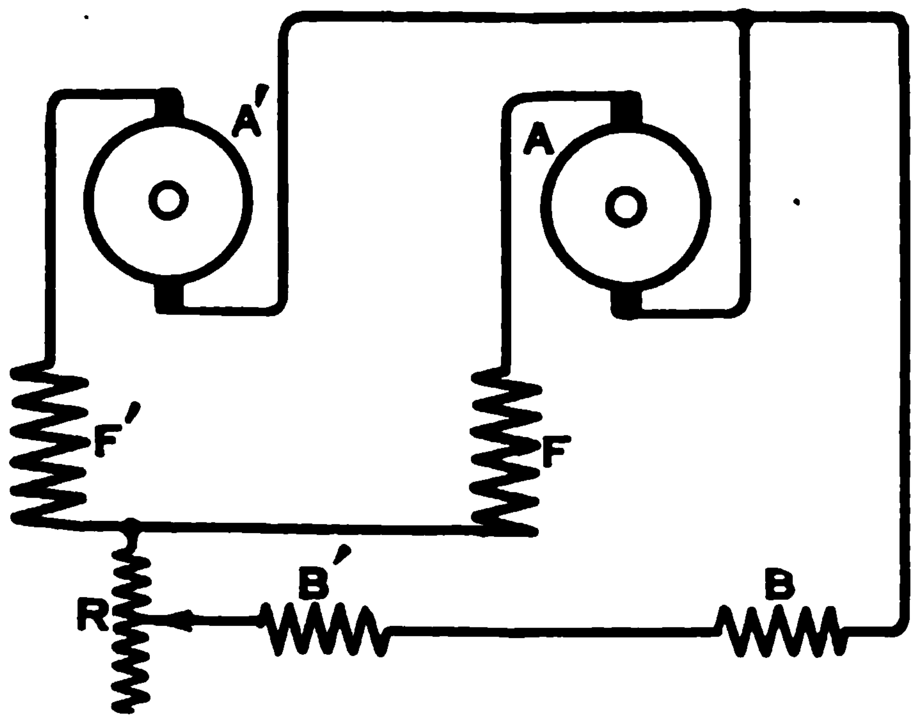


FIG. 1109.—Connections of propelling motors as generators for supplying track brakes with current and simultaneously utilizing dynamic braking.

attachments to the track brake. Current may be drawn from the line to operate this brake instead of using the motors as generators.

Regenerative Braking.—On long mountain grades where heavy trains must descend at slow speed, air brakes are not satisfactory. On electrified lines like the Chicago, Milwaukee and St. Paul, it has been found that **regenerative braking,** as it is called, which is nothing more than a special arrangement of dynamic braking, can be employed in a highly satisfactory manner, the power generated by the descending train being restored to the line in the form of electric currents of the same voltage as that supplied to the line by the power house, which

may thus be utilized in parallel with the substations to aid other trains in ascending the grade.

The plan employed on the C. M. and St. P. R. R. may be called an axle generator system. In this arrangement the main motors are separately excited from an axle generator the field of which is in turn separately supplied with current from a storage battery. The axle generator, *G*, Fig. 1110, is connected across the main motor's field, *F*, in series with a balancing resistance *R*. The main motor's armature current, when braking, is carried through this balancing resistance, thus giving a differential effect on the main motor's fields when the regenerative current in-

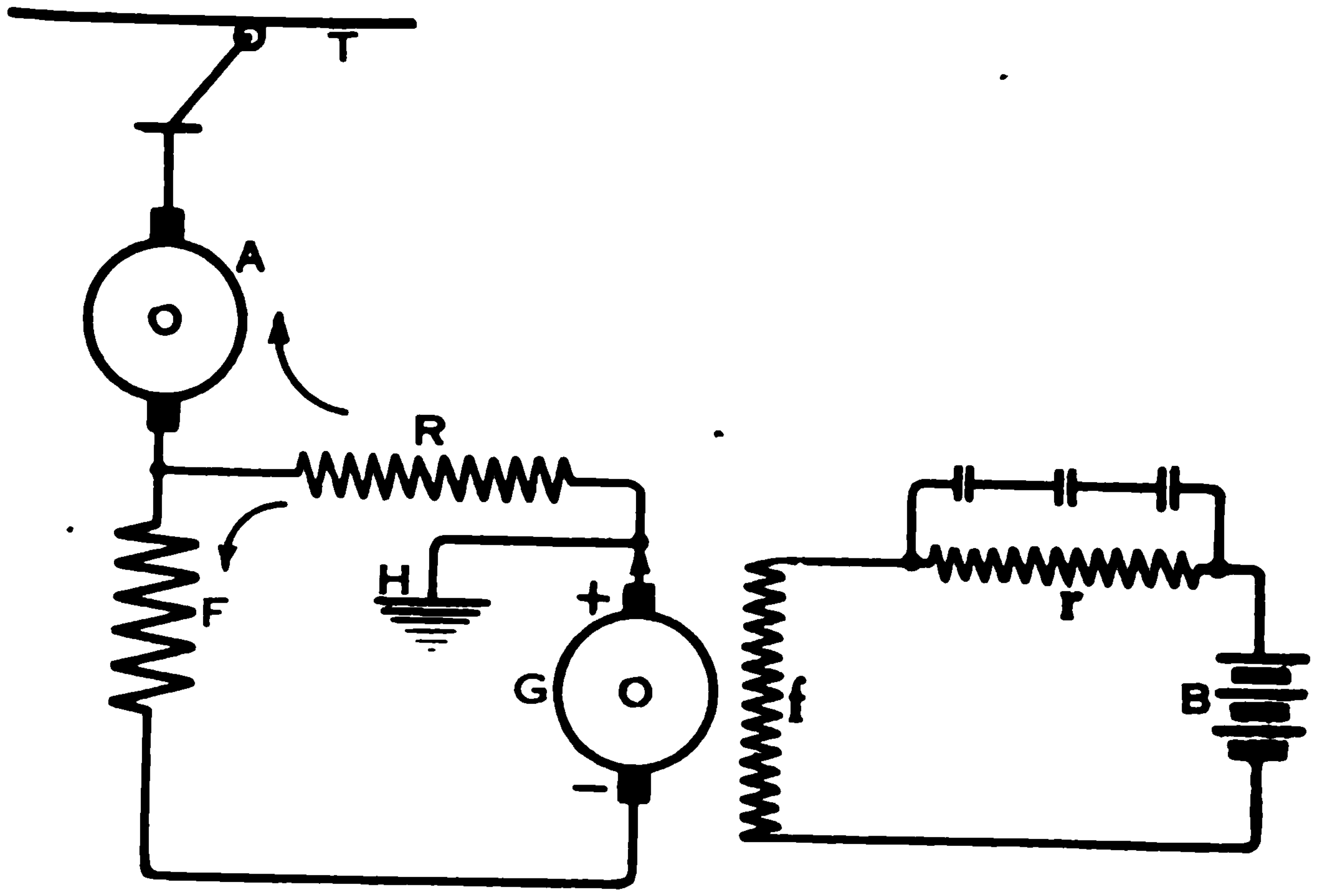


FIG. 1110.—Circuits for regenerative braking on C., M. & St. P. direct-current railway system.

creases, due to a drop in line voltage. This differential effect is necessary to stabilize the braking operation of the main motors. When absorbing power from the line, current passes from the trolley *T* down through the armature *A* and the field *F*, through *G*, and thence to the rail and ground. When braking is to occur, current from the storage battery *B* is led through a current limiting rheostat *r* and through the field *f* of the axle generator. This may be excited to such an extent as to cause current to flow from *G* into *R* and down through *F*, raising the excitation sufficiently to cause the counter e.m.f. of *A* to exceed that of the trolley, thereby forcing current back into the line which will cause braking.

In any closed circuit the sum of the voltages is zero, as, for example, in the case of a circuit from *G*, Fig. 1110, through *R* and *F*. That is, *G* has e.m.f. enough to force sufficient current through this circuit so that the *IR* drop just balances the voltage generated at *G*. If a current from some external source is drawn through *R*, the voltage available for forcing current through the circuit *G-R-F* is decreased. If, now, the speed of the locomotive increases, the voltage of the axle generator *G* increases. This raises the excitation in *F* of the main motor and increases the voltage produced in the armature *A* for braking purposes. This increases the regenerated current furnished upward through *A* to the trolley, which in turn increases the braking effect. It is evident that a large increase in braking effort is accomplished with a small change in speed. If, however, there be a sudden change in line voltage, there must be a rapid and sudden method of increasing or decreasing the generated voltage of the main motor to insure the proper braking effect under such conditions. This is the object of the resistance *R*, which is positive in its action, reducing the main motor field strength with any increase in armature current and increasing the field strength with a decrease of armature current so that the braking effect for a given grade and speed is practically constant under considerable changes in line voltage.

SECTION XX CHAPTER VII

ELECTRIC RAILWAYS

ELECTRIC BRAKES

1. Explain how dynamic braking may be employed to stop a car in case the mechanical brakes fail and the power supply from the trolley is interrupted.
2. What kind of equipment is necessary, and what steps must be taken to insure the operation of dynamic braking under the above circumstances?
3. Explain the details of the Westinghouse electric track brake.
4. Explain how regenerative braking is applied to hold the trains on mountain grades on the C. M. & St. P. Railway.

STATION EQUIPMENT

CIRCUIT BREAKERS

There are two ways of automatically opening an electrical circuit when the current exceeds a predetermined amount. One is by employing the heating effect of a current, and the other by employing the magnetic effect. The heating effect is proportional to the square of the current, and the magnetic effect is proportional to the simple current. Both of these effects have been successfully used. The heating effect is utilized in the fusible cutout, the magnetic effect in the electro-magnetic

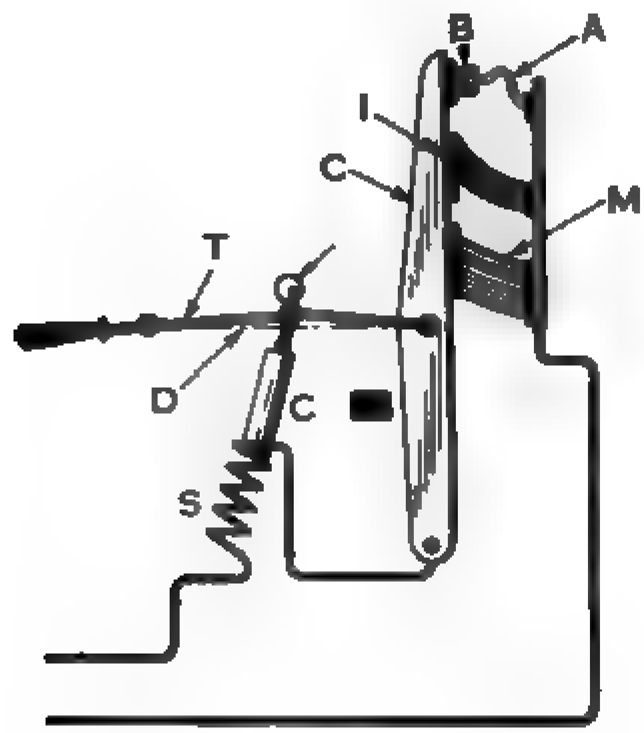


FIG. 1111.—Electro-magnetic circuit-breaker, locked closed.

circuit breaker. The fusible cutout was the first plan employed and is simple in its operation. The objection to this plan, however, is that it cannot be adjusted, nor can it be depended upon to open a circuit at any particular current. If the current is of short duration, the fuse will carry very much more than its rated capacity The magnetic circuit breaker, however, while much more expensive in point of first cost, has been refined in construction so that it is reliable and can be accurately calibrated. Furthermore, it is adjustable through a wide range;

that is, it can be set for any desired current within the limit of its capacity.

Overload Circuit Breakers.—The principle of the electro-magnetic circuit breaker may be seen from a study of Fig. 1111 Here a switch is held closed by means of a hinged arm with an eccentric stop and a toggle. This switch is provided with one or more contacts In the figure three are shown. When an overload current passes through the solenoid, *S*, the core *C* is attracted which pulls the hinged arm *D* below the center line, and a spring forces the switch open. As the switch

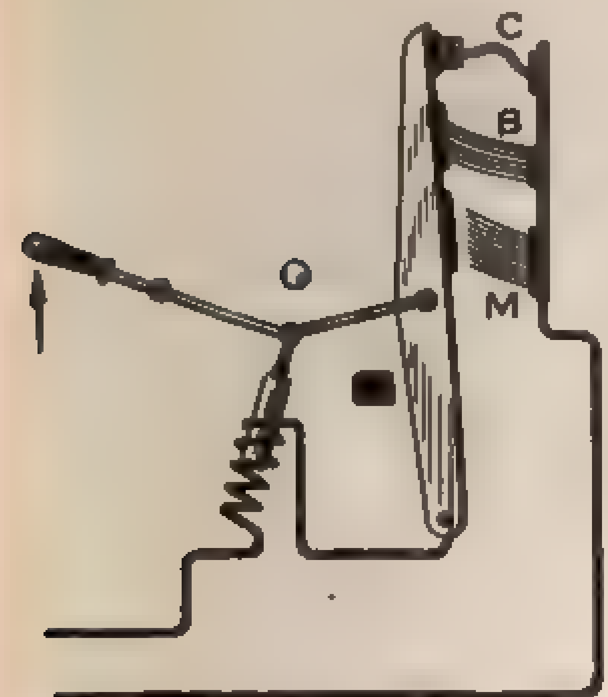


Fig. 1112.—Electro-magnetic circuit breaker in the act of opening.

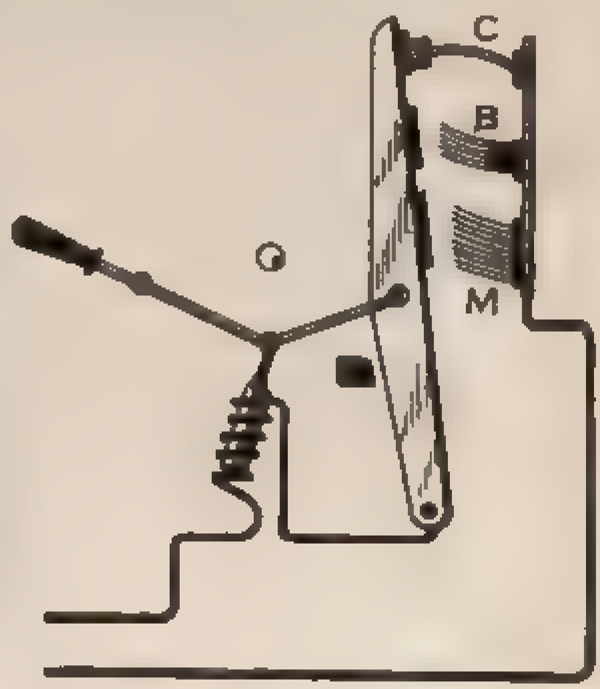


Fig. 1113.—As breaker opens the circuit is progressively transferred from *M* to *B* to *C*, each succeeding step being accompanied by reduction in current value.

starts to open, Fig. 1112, the main contact, *M*, which carries the most of the current, is interrupted first. This reduces the amount of current and compels the bypaths, *B* and *C*, to carry the remainder At the same time the circuit at *M* is interrupted without any sparking because of the bypaths. As the spring pushes the switch farther open the bypath *B* is opened, Fig 1113, and the current is now forced through the contacts at *C* which are usually of carbon. The final break is between these contacts, as in Fig. 1114 This insures that whatever arcing takes place shall be between the carbon contacts and without injury due to burning The copper faces *M-B* are thus effectu-

ally preserved from burning and pitting, with subsequent imperfect contacts due to rough surfaces.

One simple and widely used circuit breaker is shown in Fig 1115. Here the tripping coil. C is wound upon an iron core with a polar projection B. An armature, A, hinged at the back, is attracted toward the pole of the coil at front. Extensions from this armature are arranged to strike a trigger on each side which releases a toggle on a single-pole knife switch held shut by the toggle and forced open by a spring. One of these switches is in

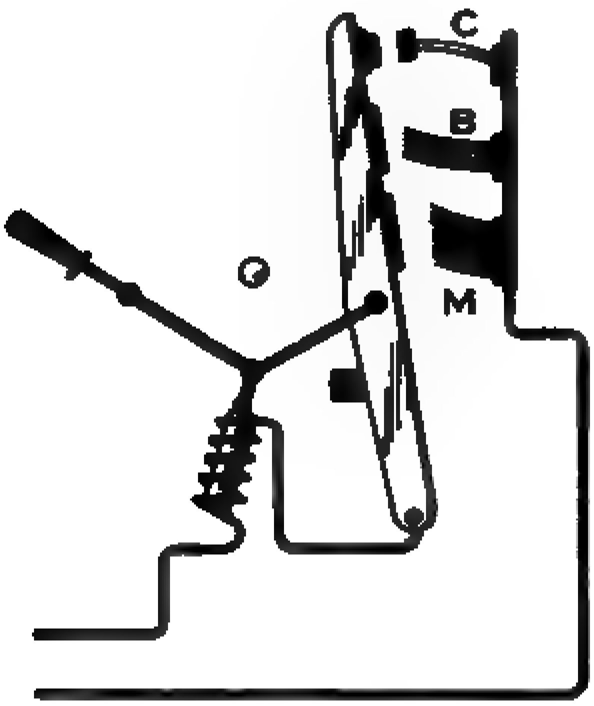


Fig. 1114.—Final break between auxiliary contacts as circuit-breaker opens

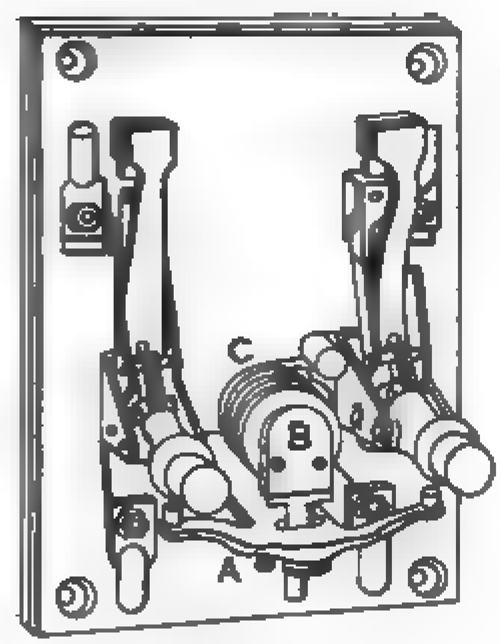


Fig. 1115.—Double-pole direct-current General-Electric circuit-breaker with separate handles for closing each line independently.

circuit with each of the two main wires, so that the breaker disconnects both wires of the circuit

No-Voltage-Release Circuit Breaker.—Instead of interrupting the line in case of overload, the circuit may be interrupted upon the failure of either line potential or line current. Fig. 1116 shows a breaker designed to open when the line potential falls below a certain value The no-voltage release coil V is connected across the line and operates by normally supporting the core of the solenoid against the force of gravity. Should the line potential fail, the core drops, tripping the toggle, and the breaker is opened by the spring Fig. 1117 shows a method of accomplishing the same result by means of a coil S in series with the line. The series coil could be very readily employed between a gen-

erator and a storage battery, charged therefrom. Should the current fall to the point where the charging ceased, the coil

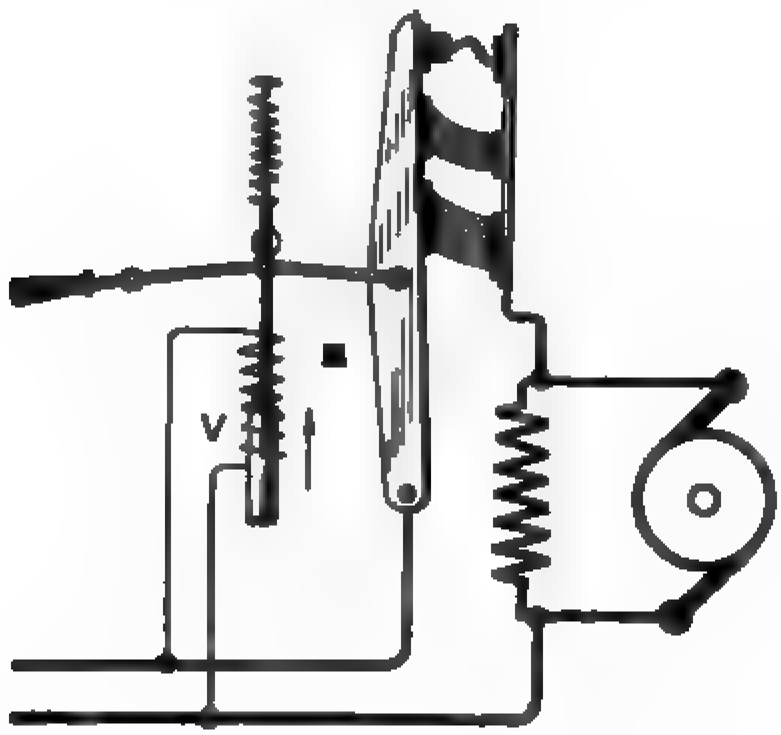


FIG. 1116.—Circuit-breaker with no-voltage release, designed to open line in case of failure of line current.

would release the core and the circuit would be broken before the battery could motor the generator.

Time-Limit Circuit Breakers.—Overload circuit breakers should be made to operate with a given current in the very least possible time. In the next place, they may be provided with a time limit. That is, when the overload occurs, instead of having a breaker open immediately, it is possible to set it so that it will not operate until two, three or more seconds have elapsed after the current rises to the amount for which the breaker is set. This is the **time-limit** type frequently used on larger power systems to insure operation of breakers in a definite sequence so that the one nearest the load

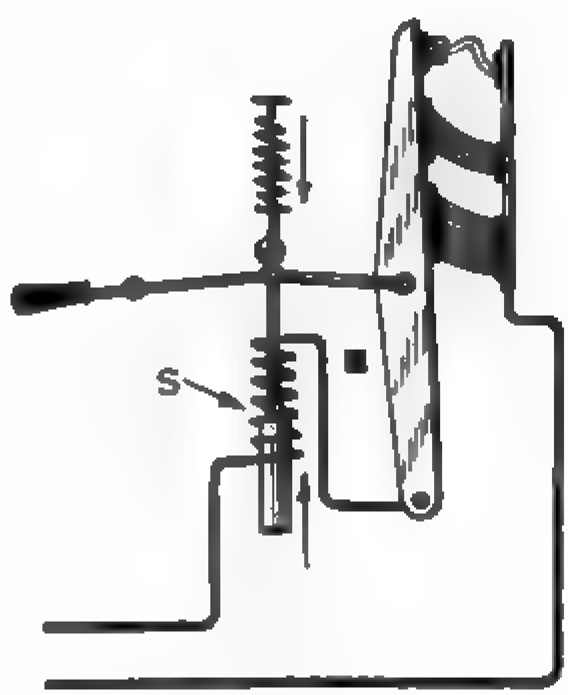


FIG. 1117.—Circuit-breaker designed to open line in case of failure of line current.

will operate first, or if that fails the one next back of that will operate, or if that fails the one still farther back toward the power station will operate.

Inverse-Time-Element Circuit Breaker.—Breakers may also be constructed on the principle of the **inverse time element.** A prominent manufacturer has adopted the letters "*I-T-E*" as the trade-mark of a breaker involving this principle. That is to say, the greater the need for the opening of the circuit the quicker it will be opened. Thus, if a breaker was set for 50 amperes and arranged to open in one-tenth of a second, should the overload rise to 100 amperes the breaker would operate in one-twentieth of a second. Thus, when the current is doubled, the time required for the circuit to open is halved.

Reverse-Power Circuit Breaker.—Where power is transmitted from a power house, *P*, Fig. 1118, to a substation *S* there are

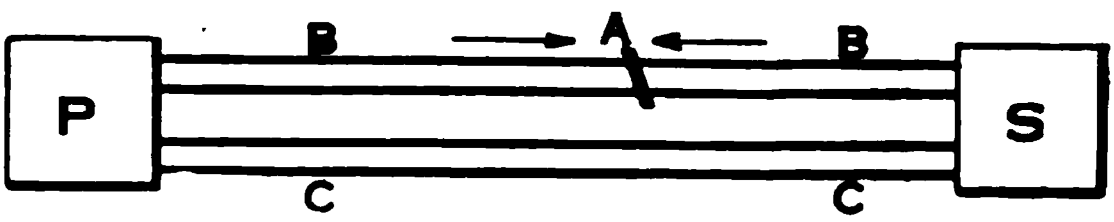


FIG. 1118.

frequently two or more transmission circuits operated in parallel. These circuits are paralleled on the bus bars both in the power station and in the substation. In case of overload at the substation on either circuit, the ordinary circuit breaker would disconnect the line. If, however, a short circuit occurred at the point *A*, power would not only flow from the power house *P* over the circuit *B* to this short circuit, but it might flow over the parallel line *C* to the substation *S*, thence through the substation bus bars and back over the circuit *B* to the short circuit at *A*. To guard against this possibility of feeding a short circuit from two directions, which might disable the whole system, and insure that the transmission line *C-C* shall be able to carry power even though *B-B* becomes disabled, the **reverse-power** circuit breaker has been devised. This consists of a relay which will maintain its contacts normally open when the flow of power is in one direction but will close the contacts on an auxiliary circuit to energize the tripping coil of a circuit breaker when the flow of power reverses.

The principle of this relay may be seen from a discussion of Fig. 1119. Such a relay must have two elements, a current element, C, and a potential element, P. Should power flow from the source S to the load L, the current at a given instant will go up through the line A, and through the coil C to the point D, through the load and back by the line E to B and the source. At the same time current in A will branch, passing up

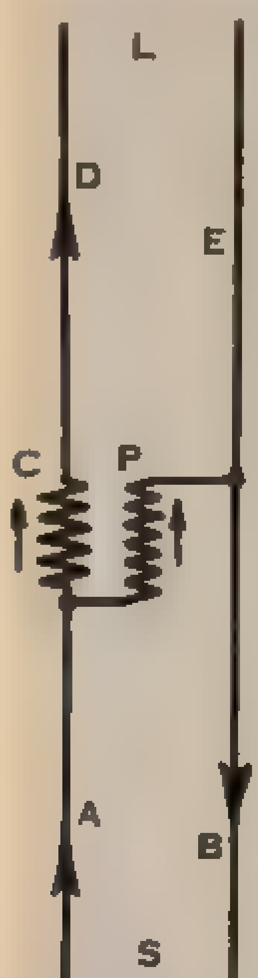


Fig. 1119.

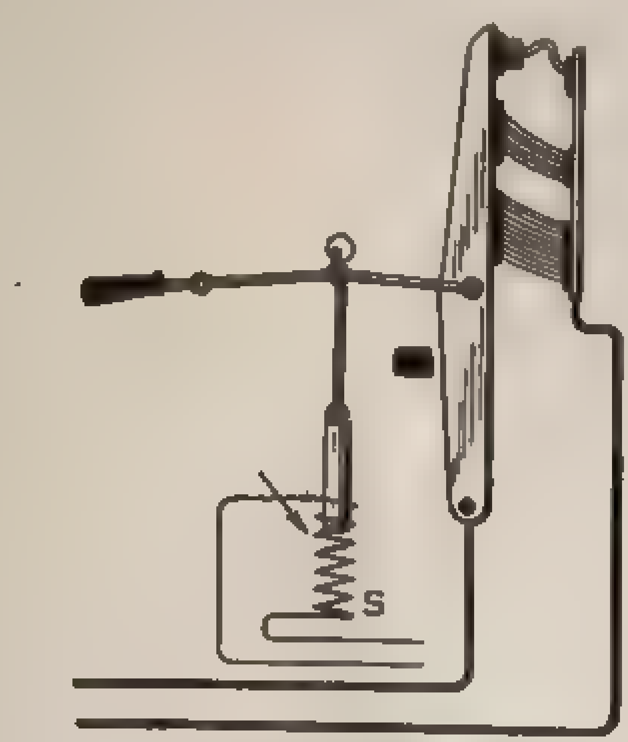


Fig. 1120.—Circuit-breaker with independent tripping coil.

through the potential coil P and back over the line B. It will be assumed that the resulting torque between these two elements will be such as to maintain the contacts of the relay open. If current reverses and goes up over the wire B to E and then back over the line D to A, the current will simultaneously reverse in P and C and there will be no reversal of torque. Thus it will be seen that this is not a reverse-current relay. If, however, the source of power should reverse from the point S to the point L, current passing down over the wire D would reverse in C and return via A-B and E, but some of the current going down through D and C would pass across and back up through P to E in the same direction as when the current originated at S. As the current is reversed in C and is not reversed in P, the relative torque between these two members is reversed and the

FIG. 1121.—Westinghouse type CR "reverse-power" relay.

device is made to close a pair of contacts which will energize an auxiliary tripping coil *S*, Fig. 1120, which would cause the circuit to be interrupted. Such a relay, designed by the Westinghouse Company, is shown in Fig. 1121. This is essentially a standard alternating current wattmeter element. A series coil and a potential coil are arranged to produce a torque which normally keeps the wattmeter disc under tension in the position shown in Fig. 1122. This causes a projecting contact to remain against a dead stop, *A*.

When the location of the source of power reverses, the torque in the relay reverses and the disc rotates in the direction of the

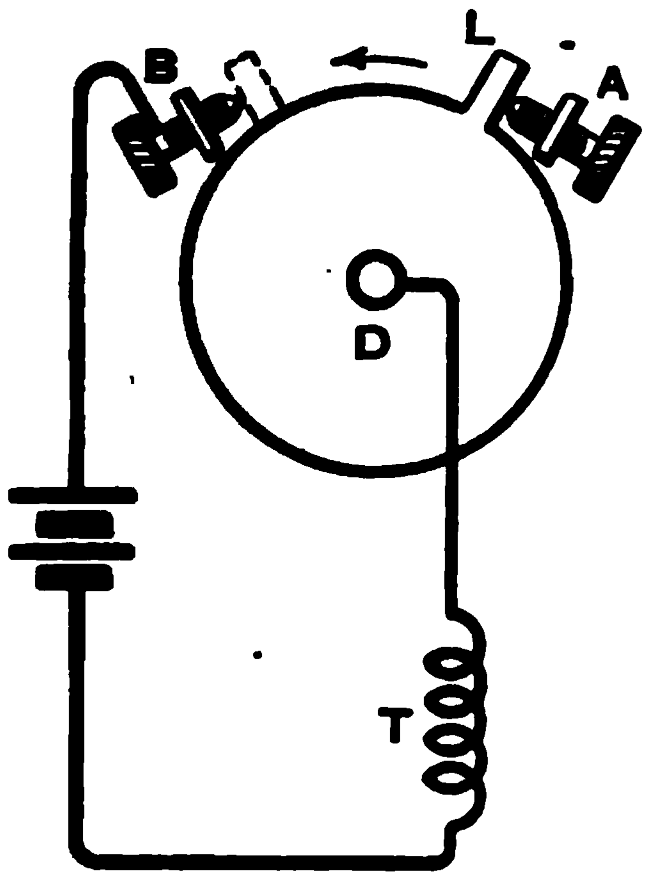


FIG. 1122.

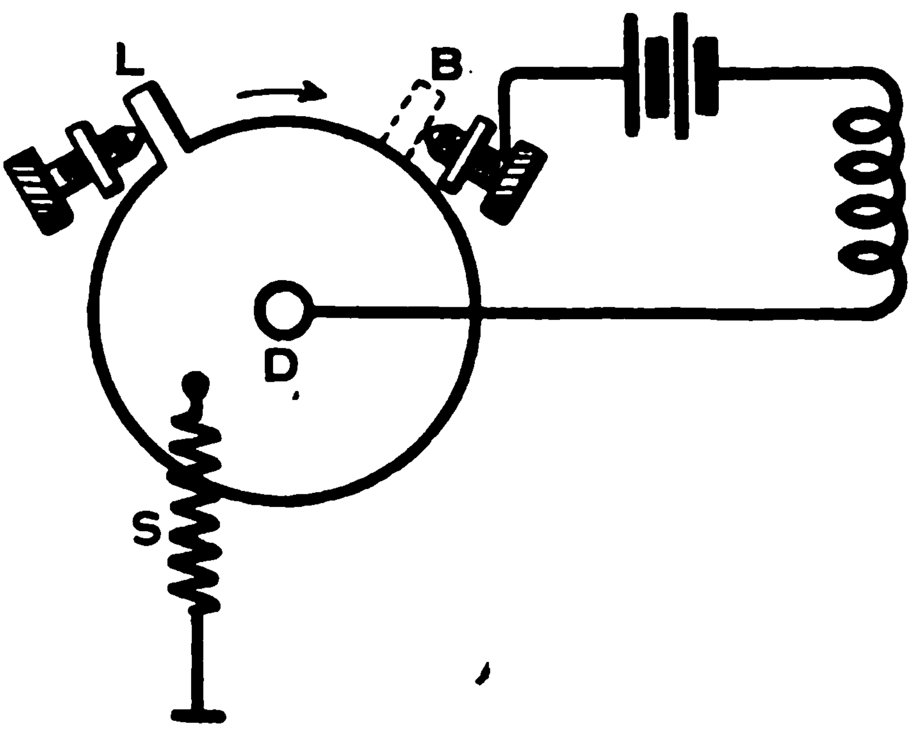


FIG. 1123.

arrow until the projecting contact *L* is brought against a live stop, *B*. This is then made to complete the circuit through some source of direct current and a trip coil *T* of a circuit breaker which opens the main line. This construction is adopted to insure that momentary reversals of power due to surges will not open the breaker. The distance between *A* and *B* is adjustable. The time required for the contact *L* to reach the stop *B* is also adjustable, for it is under control of the drag magnets of the wattmeter movement. If the drag magnets are near the circumference of the disc, the time required for the tripping coil to be closed is increased. If they are nearer the center, it is decreased. Thus with the possibility of moving the location of the contacts and varying the retardation, a wide range of adjustment is

possible. The time element feature may also be employed in connection with the wattmeter movement and an overload trip. Thus in Fig. 1123 the contact L is held against a dead stop by a spring S. As the load increases in the series coil of the wattmeter, there is a tendency for the disc to rotate toward the live contact B. This is opposed by the drag magnets. The distance between A and B, the tension of the spring and the positions of the drag magnets are all involved in the determination of the actual current and the time limit in which said current will result in tripping the main circuit.

In recent practice it is customary to employ two relays for reverse power protection, one a simple overload, inverse-time-element relay, the other a wattmeter reverse-power relay which actuates the overload relay.

Automatic Reclosing Circuit Breakers.—In certain classes of work it is desirable to have a circuit breaker automatically re-

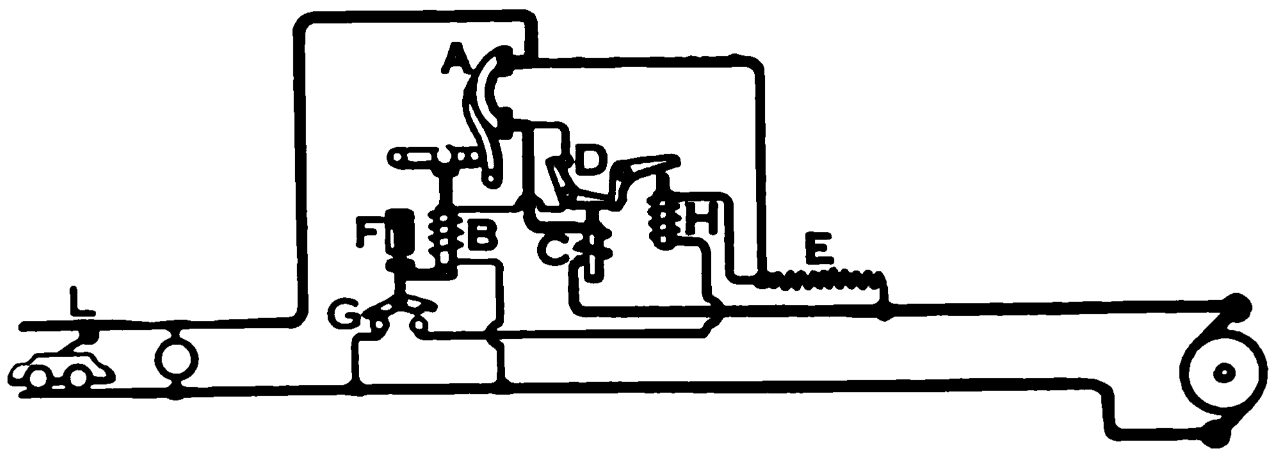


Fig. 1124.—Automatic reclosing circuit breaker for protecting mining locomotives.

close after the withdrawal of the overload which caused it to open. A breaker designed for this purpose, known as the **automatic reclosing circuit breaker,** is shown in Fig. 1124. The main contact arm of the breaker A is normally held in the closed position by means of an electro-magnet B. When an overload occurs, the current in the series coil C raises a plunger which opens a contact D in the circuit of the operating magnet B, thus cutting off the current and allowing the main contact at A to open the load circuit. A high-resistance coil E is connected in shunt to the main contacts, and a small current will now flow through E to act as an index to the condition of the line. After the opening of the main breaker and following a definite interval, a dash pot F allows a contact G to close a circuit connecting the

low-resistance trip coil H in parallel with the load circuit and in series with the high resistance E. The index current which flows through E now has two paths It can either flow through the short circuit at the load or through the trip coil H. Since the tendency is for the current to take the path of practically zero resistance, the coil H is shunted out, but the moment the short circuit is removed, current will flow readily through the coil H, which raises its core and trips a latch which closes the contact D and allows current to again flow through C and D and the closing coil B, which closes the breaker at A and power is again restored to the line.

This same principle may be applied for stationary motors so that the breaker will open either through overload or failure

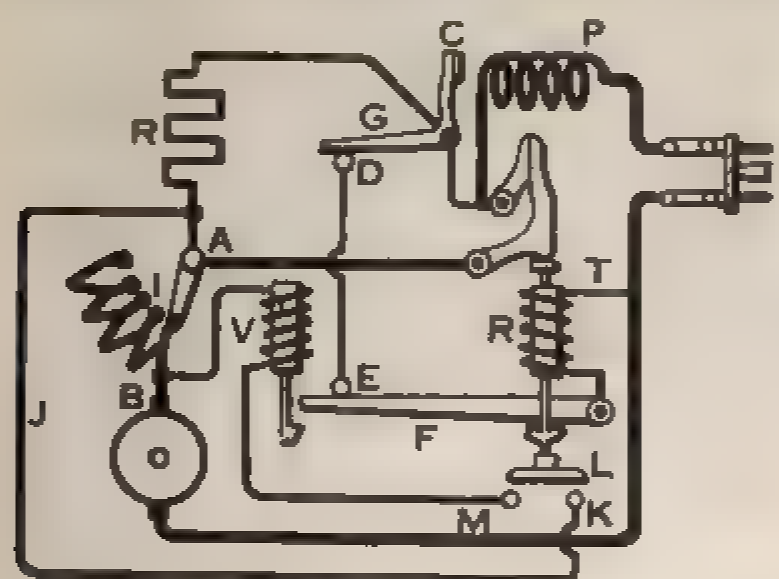


FIG. 1125. Automatic reclosing circuit breaker for protection of stationary motors: closed position.

of line voltage, and will remain open as long as the starter is in any other than the off position When the starter is returned to the off position the breaker automatically and instantly recloses.

In Fig. 1125 current passes from the main switch through the overload and blow-out coil P, through the main contacts of the breaker to the point A, through the starting box lever I to the point B, through the motor to the negative side of the line. The breaker is held closed by the operating coil R, the circuit of which is completed through G, D, E, R and T When an overload occurs the armature C is attracted, contact is broken at the point D, the coil R is de-energized and the main contacts of

the breaker open When this occurs the contact at *E* in the operating coil circuit also opens, for the lever *F* falls so that when the motor circuit is completely opened and the armature *C* drops back again closing the contacts at *D*, the contact at *E* in the operating circuit still remains open The condition of the circuits is now shown in Fig 1126. The breaker cannot be reclosed until the contact at *E* is closed, and the contact at *E* cannot be closed until the trip coil *V* is energized to lift the member *F* The trip coil *V* is short-circuited by the path *M-K-J-A-I-B*, so that it cannot be energized as long as the starting resistance is cut out If, however, the lever *I* is moved back automatically or by hand to the "off" position, then cur-

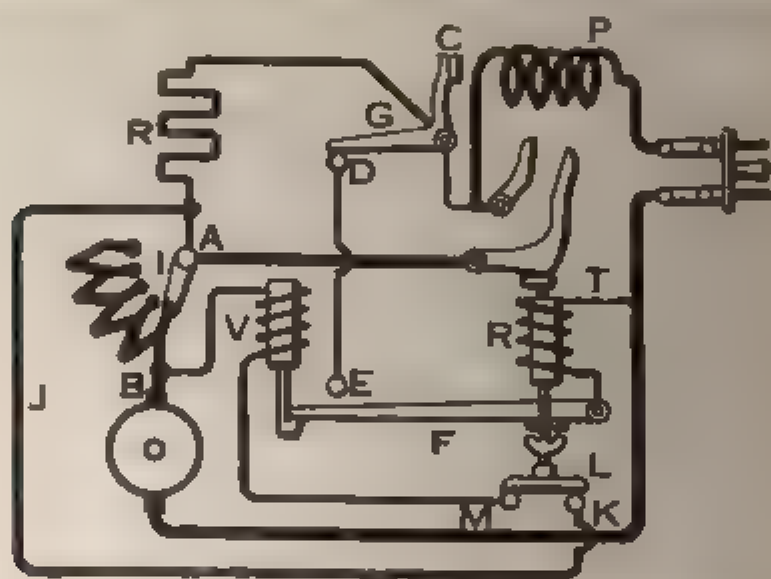


Fig 1126 —Automatic reclosing circuit breaker for protection of stationary motors, tripped open through overload

rent may flow through the coil *P* and circuit *R-J-K-L-M-V-B*, and armature, to negative side of the line When *V* now operates, *F* is brought up into contact with *E*, and current may now flow through *P-G-D-E-F-R* and *T* and close the breaker.

Open switches and circuit breakers become a menace to the safety of the station operator when the voltage of the system exceeds the neighborhood of 1,000 volts Moreover, difficulties encountered in the insulation of the current carrying parts which pass through the slate or marble panel, make this plan of mounting impractical for such pressures For such voltages it is usual to provide **oil switches** in which the contacts are removed from the front of the board to a tank in the rear where

the actual break is made under oil These switches are operated either mechanically through bell cranks or electrically through solenoids Fig 1127 shows a Westinghouse oil switch of moderate capacity The switch is closed by energizing the large closing coil *A* which attracts its core *C* The switch is held closed by a latch *L*. It is opened by energizing the small trip coil *B*, which releases the latch and permits the coiled spring *S*

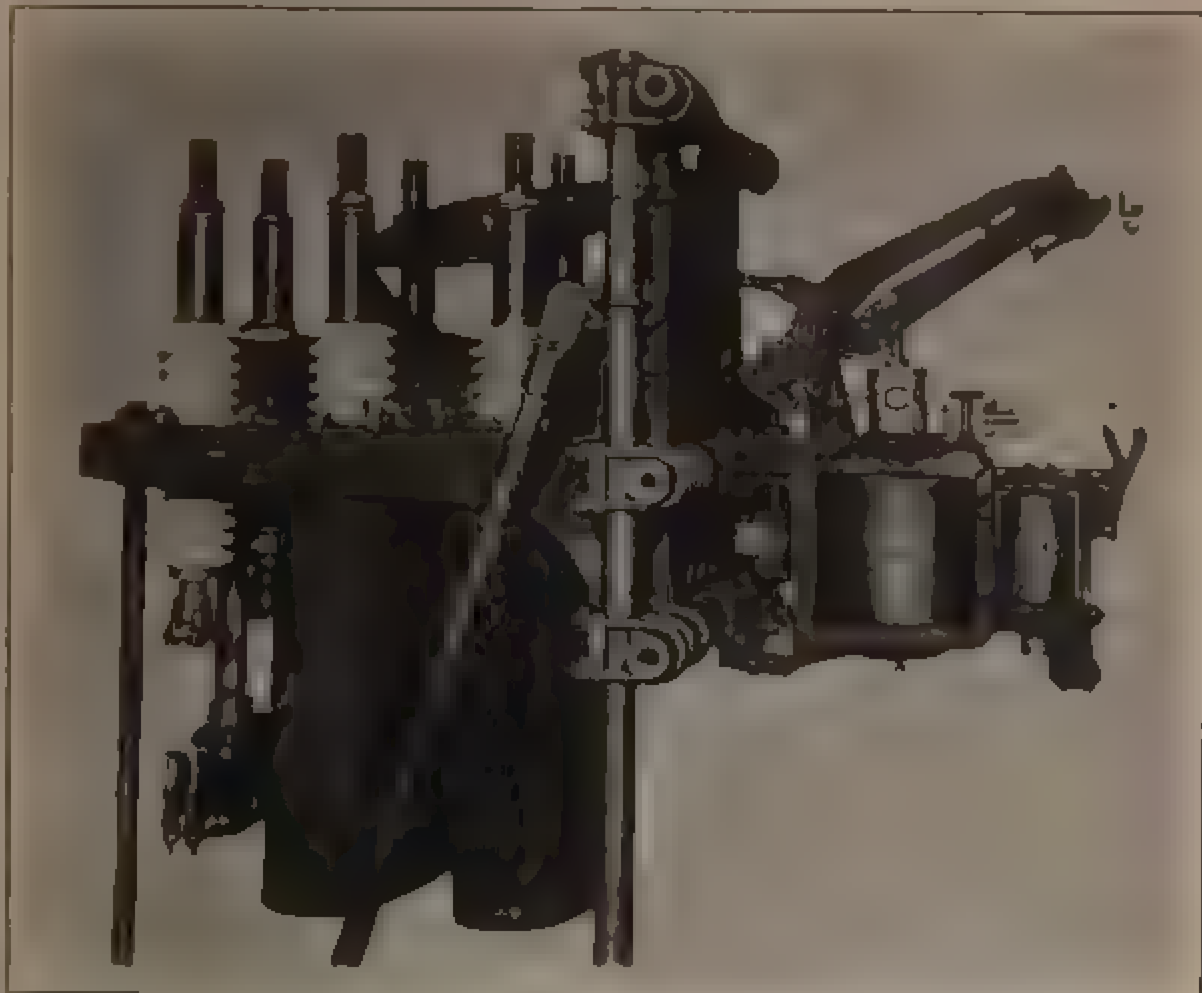


Fig 1127 —Electrically controlled oil-switch built by the Westinghouse Electric and Manufacturing Company.

to open the contacts Since the actual break is under oil, no arcing can occur, which is a very desirable feature for some applications.

The switch just shown is not adapted for heavy duty or very high voltages Fig 1128 shows a switch made by the General Electric Company for voltages in the neighborhood of 15,000. Each line is broken in two places, and each break is made in a separate tank under oil The arcing tips are renewable in case of damage. This switch is operated by springs which are com-

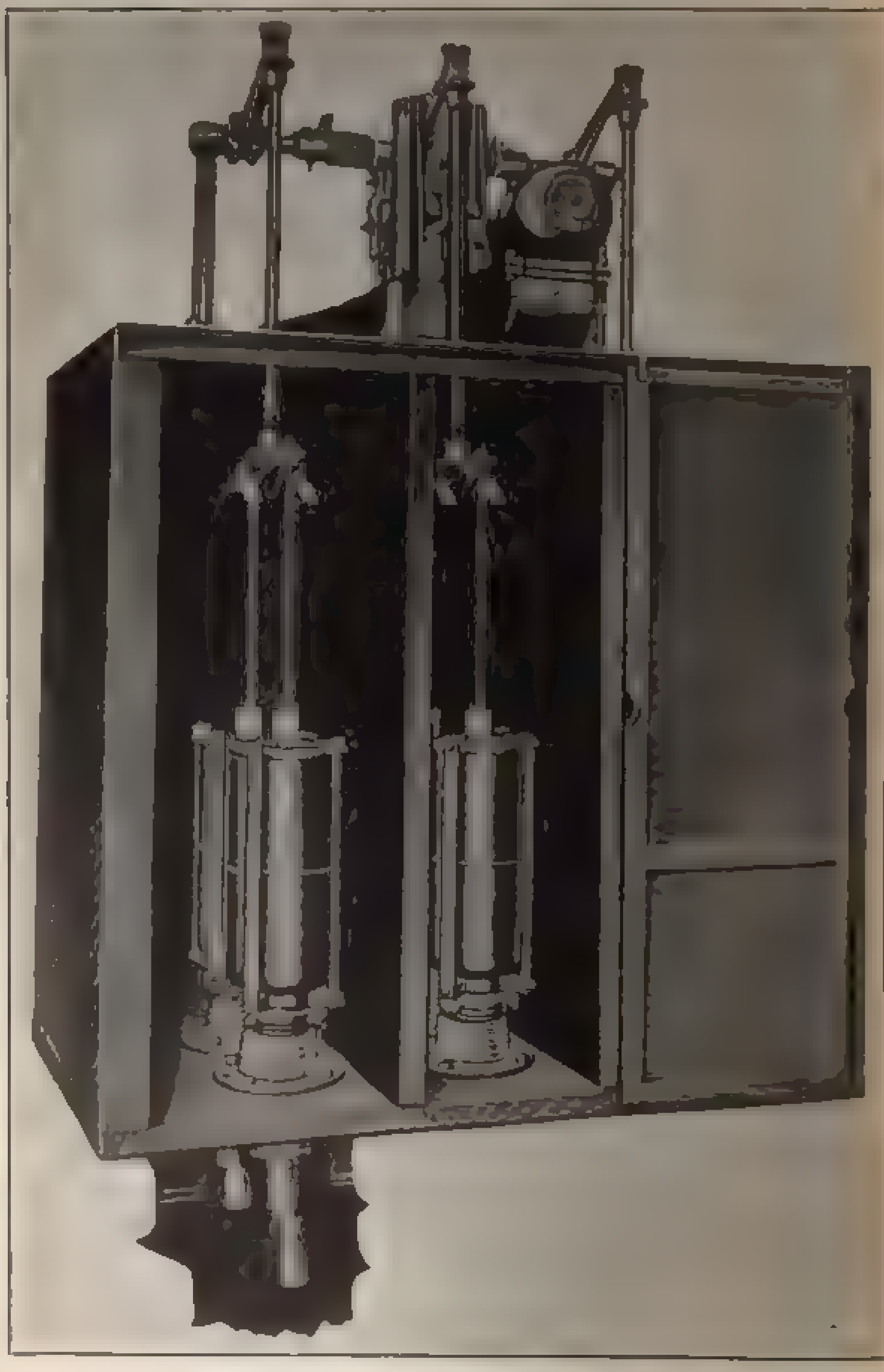


FIG. 1128.—15,000 volt, 400-amperes oil circuit breaker, built by the General Electric Company.

pressed by a motor and tripped by a solenoid. For extra-heavy duty these switches have heavy laminated surfaces for the main break, although the final rupture occurs at the arcing tips. The Westinghouse Company builds a switch for similar duty which is solenoid operated.

Oil switches are usually so connected that they act as circuit breakers as well as switches. This is accomplished by connecting the trip coil through overload or reverse power relays, which open the switch when an overload comes on, or on reversal of power in the line.

Open air switches have been designed for high potentials. Such switches are usually mounted outdoors, where there is plenty of space, and have abnormally large clearances when open. The break is usually made over horn gaps which tend to minimize the line disturbances due to switching operations. These switches are not well adapted for indoor mounting, and are hand operated by mechanical linkage.

SECTION XXI CHAPTER I

STATION EQUIPMENT

CIRCUIT BREAKERS

1. **Explain** the principle of the electromagnetic overload circuit breaker. **Sketch.**

2. **What provision** is made to avoid burning the main contacts when the **circuit breaker** opens under heavy load?

3. Explain the principle of the no-voltage-release circuit breaker. Sketch.

4. Explain the principle of the "time-limit" circuit breaker.

5. Explain the principle of the "inverse-time-limit" circuit breaker.

6. Explain the object and principle of the "reverse power" circuit breaker. Give elementary sketch showing principle.

7. Explain the plan of the Westinghouse type CR. relay.

8. How is the Westinghouse type CR. relay designed and adjusted for both reverse power and time limit overload?

9. Explain the general principle of the automatic reclosing circuit breaker Where is it used?

STATION EQUIPMENT

LIGHTNING ARRESTERS

The object of a lightning arrester is twofold: First, to relieve the line of high potential charges, and second, to prevent the flow of an abnormal generator current in the path of the discharge In its simplest form it is shown in Fig 1129 Here a simple gap consisting of a series of sharp metallic teeth is connected on one side to the line and on the other side to the ground. When a lightning discharge comes in over the line *E*, its objective is the earth It would naturally flow into the generator *G*, where it would puncture the insulation at some weak point and then pass from the frame to the ground. If a choke coil *L* is interposed

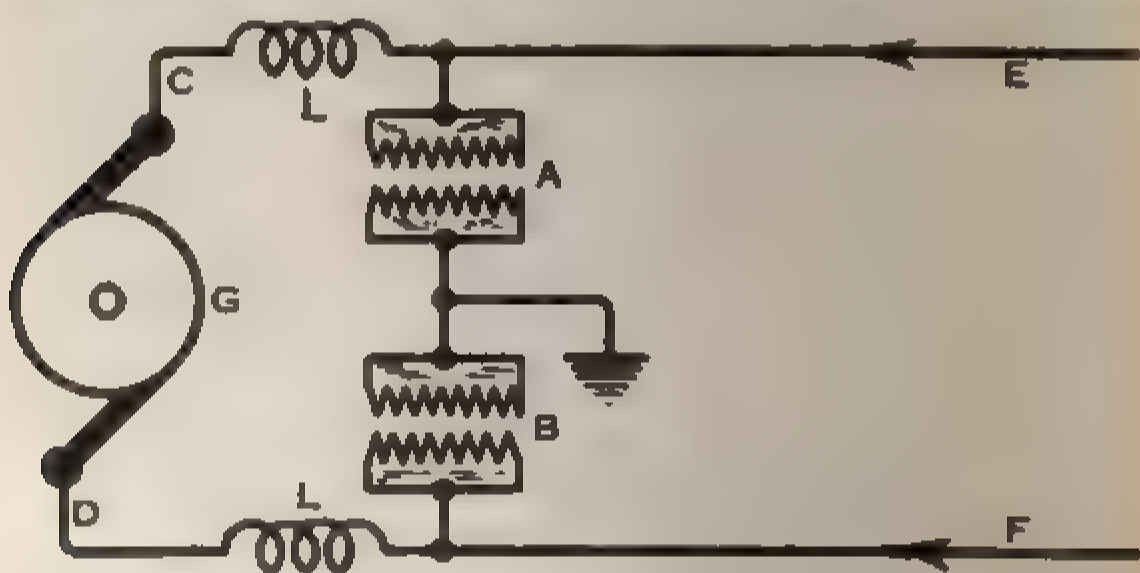


FIG. 1129. —Elementary form of lightning arrester.

between the generator and the line, its high reactance acts as a barrier to the passage of the lightning discharge, which is of high frequency. As the discharge surges up against *L* the effect is very much like an ocean wave coming up against a breakwater. It causes a splash. If there is a bypath closely adjacent thereto, including a gap connecting to the ground, the high potential is enabled to bridge this gap and the line is discharged. If a discharge comes in over the line *F*, it is likewise backed out by the choke coil on this side and diverted by the gap *B* to the ground This was the form of arrester first used

for telegraph and telephone lines. Where generator currents are involved, however, it is possible for the current to find a path over the conducting spark so that it may flow from *G* through *C-L-A-B-L* and *D*. This would cause heavy arcs at *A* and *B*, which would destroy the arrester and short-circuit the generator. A successful arrester must pass lightning discharges to ground with the utmost freedom, but it must positively rupture any arc established by generator current or prevent the production of the arc entirely.

General Electric D.C. Arrester.—One of the commonly used arresters for direct current is shown in Fig. 1130. Should a lightning discharge come over the line *L* and encounter a choke coil at *A*, it is diverted through the gap *B*, whence it may pass through a high-resistance graphite rod *E-F* to the ground. Should generator current follow in the path of this discharge and produce an arc, it takes the low-resistance path through the coil *C* in preference to the high-resistance portion *E* of the graphite rod. The drop in potential across the extremities of this coil due to *E* is sufficient to powerfully energize it. A heavy flux is therefore produced across the pole pieces *H-K* of this magnet at right angles to the spark gap. The magnetic flux quickly and effectually extinguishes the arc. The path *C* is of high inductance but low resistance. The path *E* is of high resistance but low inductance. The generator current therefore readily follows *C* but ignores *E*. The lightning discharge prefers *E* and ignores *C*. The section *F* is of sufficient resistance to limit to a moderate value the actual generator current which may pass to the ground. This arrester has been successfully used for low potential circuits and especially for railway lines.

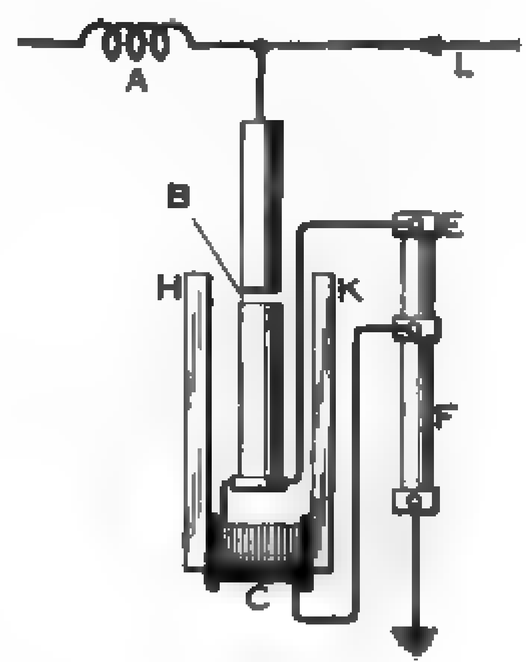


FIG. 1130.—General Electric magnetic blow-out, direct-current lightning arrester.

The Garton-Daniels D.C. Arrester.—Another form of arrester is shown in Fig. 1131. A lightning discharge, coming over the line *L* and barred by the choke coil *A*, passes through the high-

resistance rod *E-F* and thence by a flexible lead *D* to a brass rod *K* which is connected to an iron core at the bottom of the solenoid *C*, and then jumps a small gap between the two carbon rods at the point *H* and thence passes to the ground *G*. The gap is a very small one, and lightning discharges pass readily to ground. Should generator current follow in the path of the discharge, it passes from *B* to the coil *C* in preference to the high-resistance path *E*. This magnetizes the core and raises the plunger, drawing an arc in the bottom of the tube in series with the external arc at *H*. The effect of this second arc is to immediately extinguish the one at *H*. Both arcs therefore fail, all current ceases, and the plunger drops back into its original position ready for another discharge.

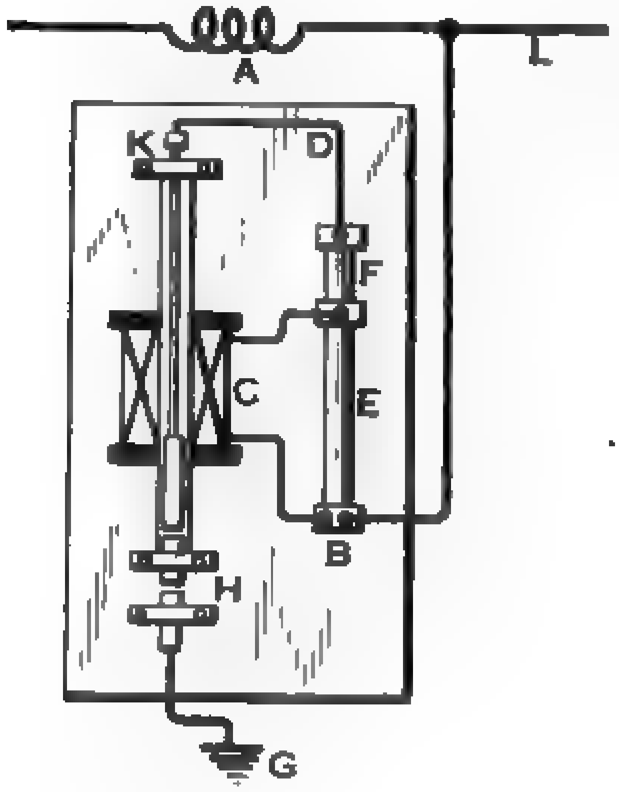


FIG. 1131.—Garton-Daniels direct-current lightning arrester.

The Wurts Non-Arcing A. C. Arrester.—The arresters for alternating currents are designed in a different way. The Wurts non-arcing arrester, manufactured by the Westinghouse Company, is shown in Fig 1132. In its original form this arrester consisted of seven cylinders mounted vertically and free to be rotated between porcelain supports at the top and bottom. The two outside cylinders were connected to the lines, while the middle cylinder was connected to the ground. The distance between these cylinders was approximately $\frac{1}{32}$ of an inch. If a discharge came in over

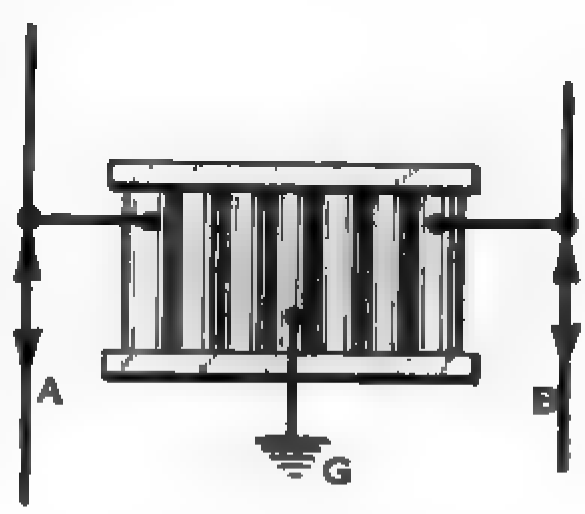


FIG. 1132.—"Wurts" non-arcing alternating-current lightning arrester, built by the Westinghouse Company.

the wire A, it jumped three gaps in series to the ground. If a discharge came in over the wire B, it likewise jumped three gaps and passed to the ground. If discharges came in simultaneously from A and B, a discharge would be established between the two line wires. With any other device such sparks would constitute a short circuit across the line and a heavy arc would be established. These cylinders, however, are constructed of an alloy containing zinc, cadmium, bismuth and antimony. This is known as a non-arcing metal; that is, it is difficult for an arc to be maintained between electrodes of this character. Should an arc start, there is immediately formed a non-conducting film of oxide vapor which instantly suppresses the arc. A peculiar feature of the arrester is that, while an arc cannot be maintained across a gap $\frac{1}{32}$ of an inch in length, if the distance is increased to $\frac{1}{8}$ of an inch, vicious arcing will ensue.

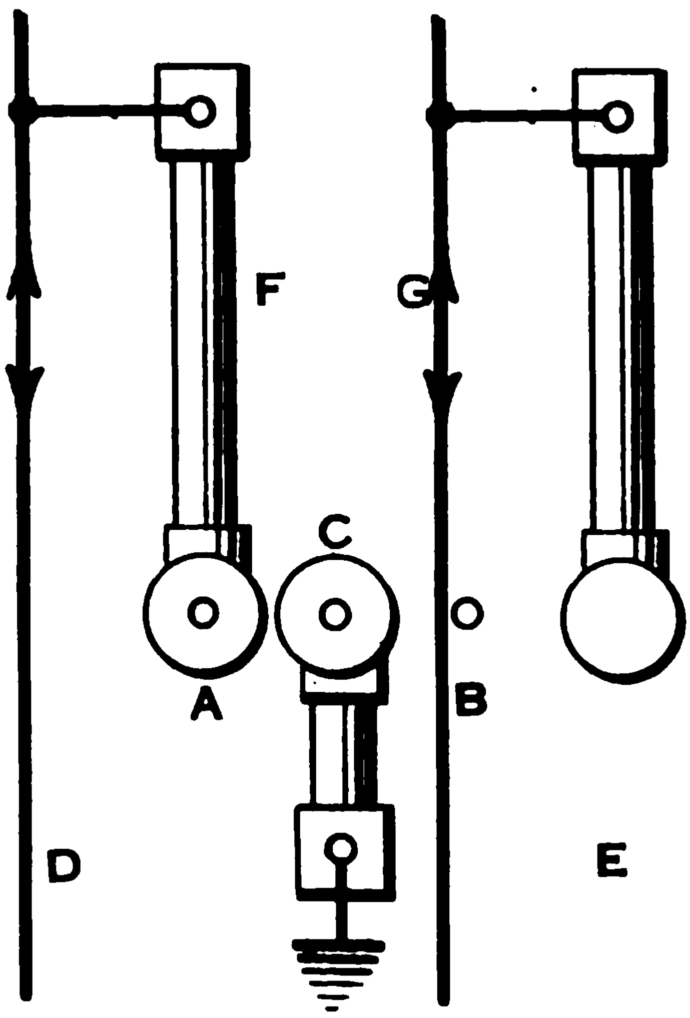


FIG. 1133.—General Electric non-arcing alternating-current lightning arrester.

The General Electric Non-Arcing A. C. Arrester.—The General Electric non-arcing arrester for A.C. is shown in Fig. 1133. Here, brass cylinders A-B-C of relatively large diameter and short length are mounted so that they furnish two gaps between the lines D and E with high-resistance graphite rods F and G in series. Should a lightning discharge pass these two gaps simultaneously and thus connect the lines D-E, the current which flows will be limited by the resistance of the rods F-G in series. A wave of current on a 60-cycle circuit cannot last more than $\frac{1}{120}$ of a second. The large cooling surface afforded by these cylinders is such that in this brief interval of time the metal cannot be raised to the volatilizing temperature. Without the metallic vapor no conducting path is provided. Hence, when the current passes through the zero point of the wave the spark ceases and the circuit is interrupted.

The General Electric "Shunted Gap" Arrester.—An alternating-current arrester embodying novel features is the **shunted gap** arrester which was produced by the General Electric Company in 1907. About that time it was discovered that an arc, which is exceedingly unstable anyhow, may be extinguished by placing a properly proportioned resistance in shunt therewith. Thus, for example, under certain conditions it is impossible to maintain an arc across a gap $\frac{1}{32}$ of an inch long if that gap is shunted by 5 ohms resistance.

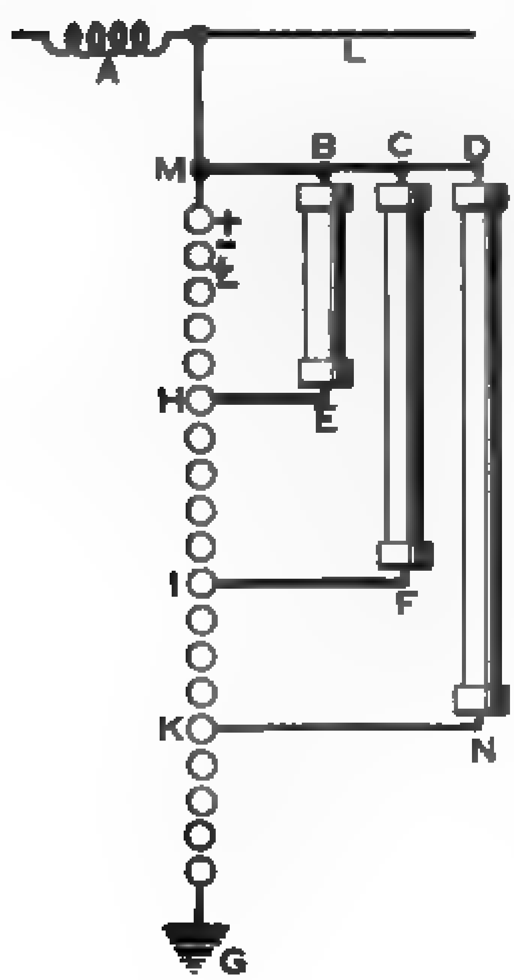


Fig. 1134.—Principle of General Electric "shunted-gap" lightning arrester.

In this arrester there is a series of gaps between the line and the ground with graded resistances placed in shunt with certain gaps, as in Fig. 1134. The cylinders of a multi-gap arrester act like the plates of a condenser in series. Let a pressure be applied to this arrester from the line *L*. If the top cylinder is positive, it will induce a negative charge on the upper edge of the adjacent cylinder and repel an equal positive charge to the lower edge. This cylinder will induce similar charges on the one next below it and that in turn on the one below it, but each charge on each succeeding cylinder, counting from the top of the arrester down, will have a slightly smaller charge induced than the preceding one. The quantity induced on the second cylinder from the top is greater than that on any lower cylinder, and its gap has a greater potential strain across it. When the potential across the first gap is sufficient to spark, the cylinder next below is charged to line potential, and the second gap receives the same static strain as the first and breaks down. The successive action is similar to knocking down the first one of a row of blocks in which each succeeding block pushes against the next one. This action explains why 16 gaps $\frac{1}{16}$ of an inch long require less

potential to break them down in series than one gap one inch long. When sparks are produced across all of the gaps in series, generator current may flow in the path of the discharge. This current is of relatively high amperage, and the distribution of potential along the gaps now equalizes and is simply that necessary to maintain an arc across each gap. The generator current will continue to flow until the potential of the alternator passes through zero at the end of an alternation when the arc extinguishing quality of the metal cylinders comes into play. The greater the magnitude of the generator current the greater the number of gaps required to extinguish the arc.

The number of gaps a given voltage can break down in series increases very rapidly with the frequency. In the shunted gap arrester a bypath of high resistance around the gaps is provided so that the series resistance will be automatically reduced if safety demands it, on account of a severe lightning discharge. At the same time paths are provided for a wide range of frequencies. This type of arrester may be considered as four arresters in one.

First, for small discharges there are a few gaps in series between *K* and *G* and a high resistance *D-N* in circuit between line and ground. This circuit will discharge accumulated static strains and also all disruptive discharges of small ampere capacity.

Second, there is a larger number of gaps, *I-G*, in series with a medium resistance graphite rod *C-F*. This will discharge disruptive charges of medium ampere capacity.

Third, there is a still greater number of gaps, *H-G*, in series with a small resistance unit *B-E*, which will care for heavy disruptive discharges.

Fourth, the entire series of gaps, *M-H-I-K-G*, with no other high resistance in series provides a path through which the heaviest lightning discharges may freely pass.

In each of these four circuits the number of gaps and the resistances in shunt therewith are so proportioned as to insure the extinguishing of the arc due to generator current at the end of the half cycle in which the lightning discharge takes place.

The superiority of this arrester is due largely to the proper shunting of its gaps. It will relieve the line of either light or heavy lightning discharges throughout a wide range of frequencies, the groups of gaps being so proportioned to the shunt

resistance that the rectifying quality of the cylinders readily extinguishes the arc Fig 1135 shows the actual appearance of the General Electric Shunted Gap Arrester.

Fig. 1135 —General-Electric shunted gap A C lightning arrester.

The Electrolytic Aluminum Cell Lightning Arrester.—For high-voltage lines the electrolytic aluminum cell lightning arrester has come into wide use This consists of a stack of aluminum cells or cones arranged as shown in Fig 1136. These cones are separated a small distance from each other and are filled with an electrolyte The lowest cone connects to the ground and the upper cone through a small gap to the line. When an alternating current is passed through this stack of cones there is developed a high-resistance film of aluminum hydroxide on each side of each cone which will withstand a pressure up to 300 volts A C and 420 volts D C To withstand a line pressure of 60,000 volts it is necessary to install $\frac{60,000}{300} = 200$ cells in series between each line and ground The resistance offered to the passage of current is about 30,000 ohms per square inch If the pressure on the line goes up to 90,000 volts, the high-resistance film is immediately broken down and the resistance drops almost instantly to about 10 ohms per square inch This permits a free discharge of static to ground until the potential falls to normal, when the high resistance is again restored The device behaves precisely like a safety valve on a boiler. There is no arc to ground and consequently no mechanism required to extinguish it.

It has proved highly successful in all high-voltage installations. The arrester is mounted in a metallic case filled with oil There is a mall gap in series between it and the line which must be reduced in length for about one-half minute each day, which is sufficiently long to allow a charging current to pass from the line

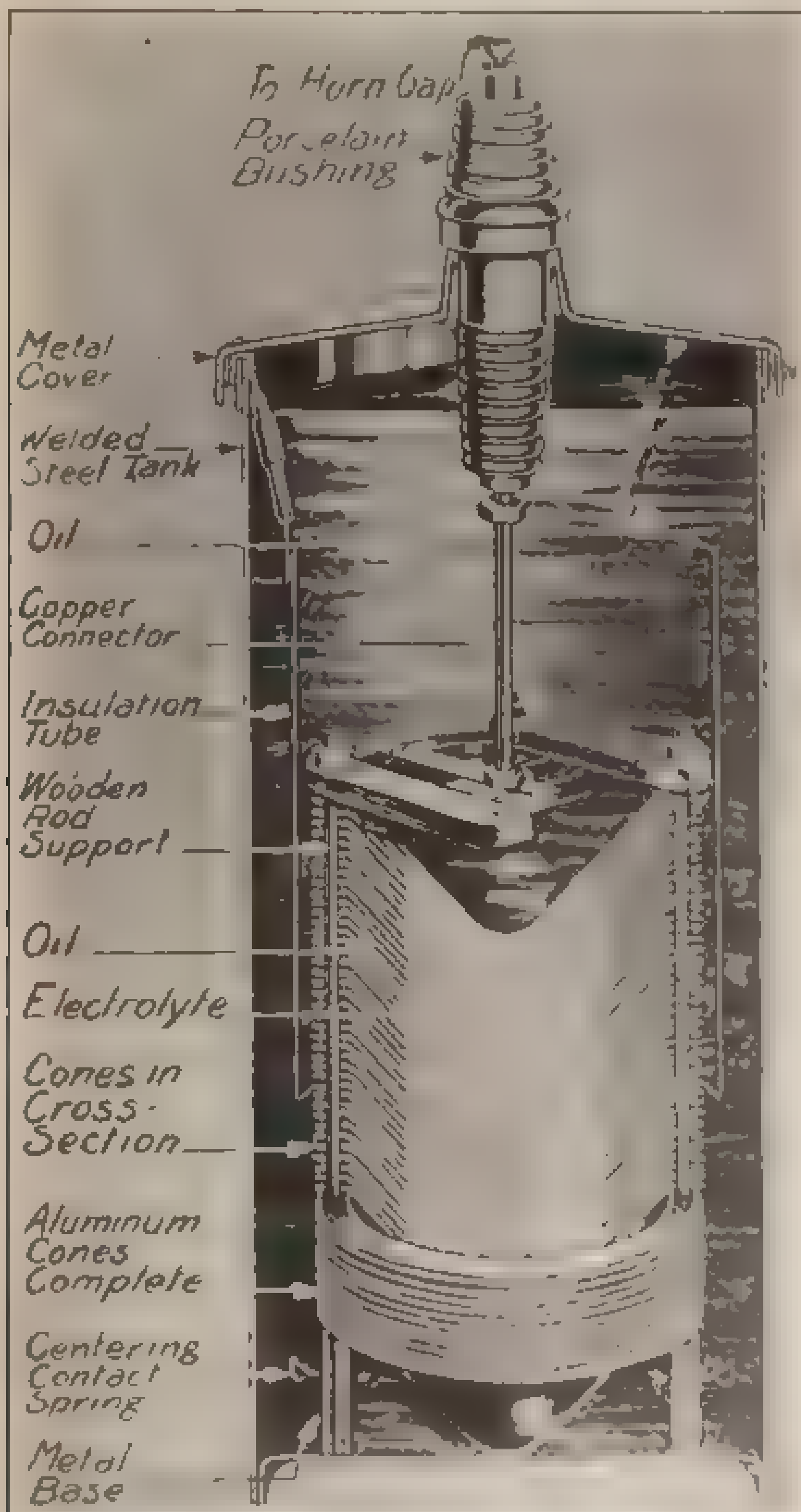


FIG. 1136.—Sectional view of aluminum cell, electrolytic lightning arrester for high-voltage circuits, built by the General-Electric Company.

through the arrester for the purpose of developing the high-resistance film. Once formed, this film will then protect the line for twenty-four hours at normal line voltage, but will quickly break down and allow the passage of all abnormal charges.

Where electrolytic arresters are used on three-phase lines it is common practice to enclose all arresters in a single grounded tank for voltages up to 13,500, Fig. 1137. For outdoor mounting and voltages above 13,500, three tanks are used if the line operates with grounded neutral. The tanks of these arresters are grounded. For lines with an ungrounded neutral, four tanks are employed, one for each leg of the line and one between the neu-

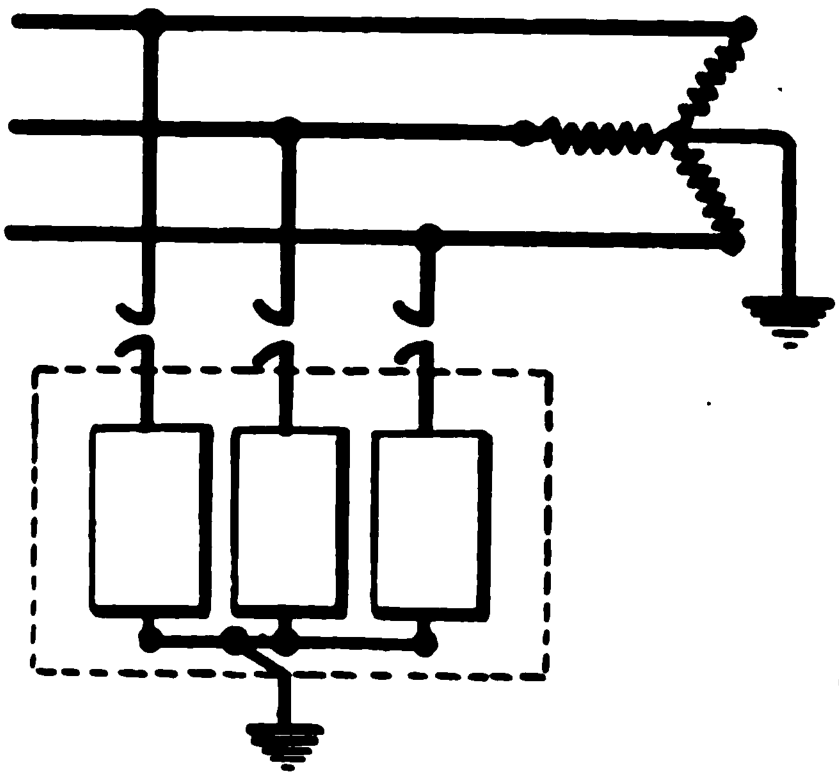


FIG. 1137.

tral of these three tanks and the ground, Fig. 1138. The tanks in this case are insulated from the ground.

Impulse Gap Arrester.—The ideal lightning arrester would be one which would enable the line to discharge the high frequency disturbances at a low voltage and at the same time offer a high resistance to potentials at normal frequency. The impulse gap, designed for use with arresters, has this selective feature to a high degree. The principle upon which this gap is constructed is as follows: Referring to Fig. 1139, *F-G* are the electrodes of the main gap. *R* is a high resistance and *K-K'* are condensers. At normal frequencies, the presence of the auxiliary electrode *F* does not affect the distribution of the electro-static field between *F* and *G* because its potential will be practically half-way between that across the gap. When a high frequency disturbance appears on the line, the resistance remains constant

in value while the capacity-reactance of the condensers decreases with the increase in frequency. This brings about a redistribution of the stresses in the electrostatic field. The resistance R, in series with the condenser K, prevents the impedance of R-K

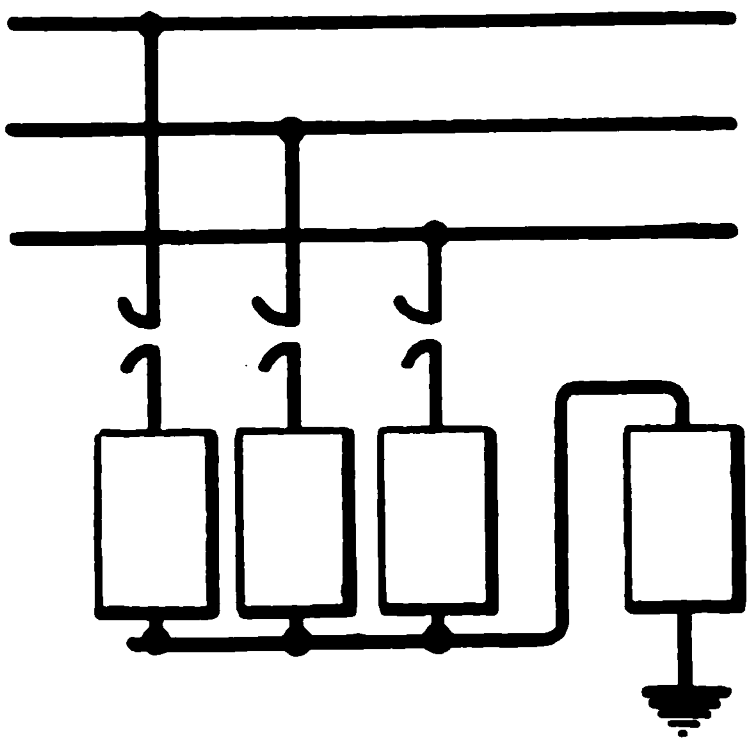


Fig. 1138.

from falling as much as that of K'. As the reactance of K' decreases, the potential across F-E falls. As the potential across F-G is constant, a fall across F-E is accompanied by a rise across E-G. The voltage across E-G will continue to rise until nearly the entire voltage appears across this section of the gap. A

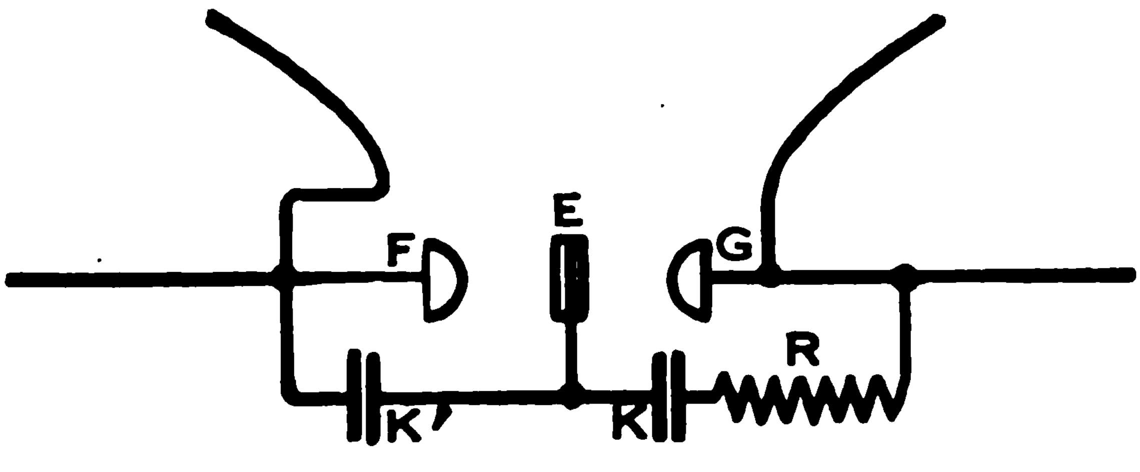


Fig. 1139.—The "impulse-gap" lightning arrester.

discharge from G to E then occurs, and the condenser K' is charged to a point where a discharge occurs between E and F. For voltages at normal line frequency the gap has the same characteristics as the usual gap without the auxiliary electrode.

The General Electric Compression-Chamber Arrester.—The compression-chamber multi-gap lightning arrester has been designed especially for use with small transformers individually

on pole line construction. Fig 1140 illustrates the General Electric Arrester of this type A large number of air gaps in series insures the prompt cutting off of generator current following a discharge, but it also tends to increase the voltage required initially to break down the arrester. This tendency is overcome by the use of conductors paralleling the gaps, which are called antennae and are connected to the ground. These antennae give a condenser effect and cause the discharge to rapidly pass across the gaps. The arrester thus has the advantage of both a large number of gaps as far as rupturing the generator arc is concerned, and a small number of gaps as far as the breaking-down point for static discharges is concerned The gaps are enclosed in an air-tight chamber, and when a discharge takes place the gas formed in the gaps is compressed This aids the rectifying action of the gases in promptly extinguishing the arc.

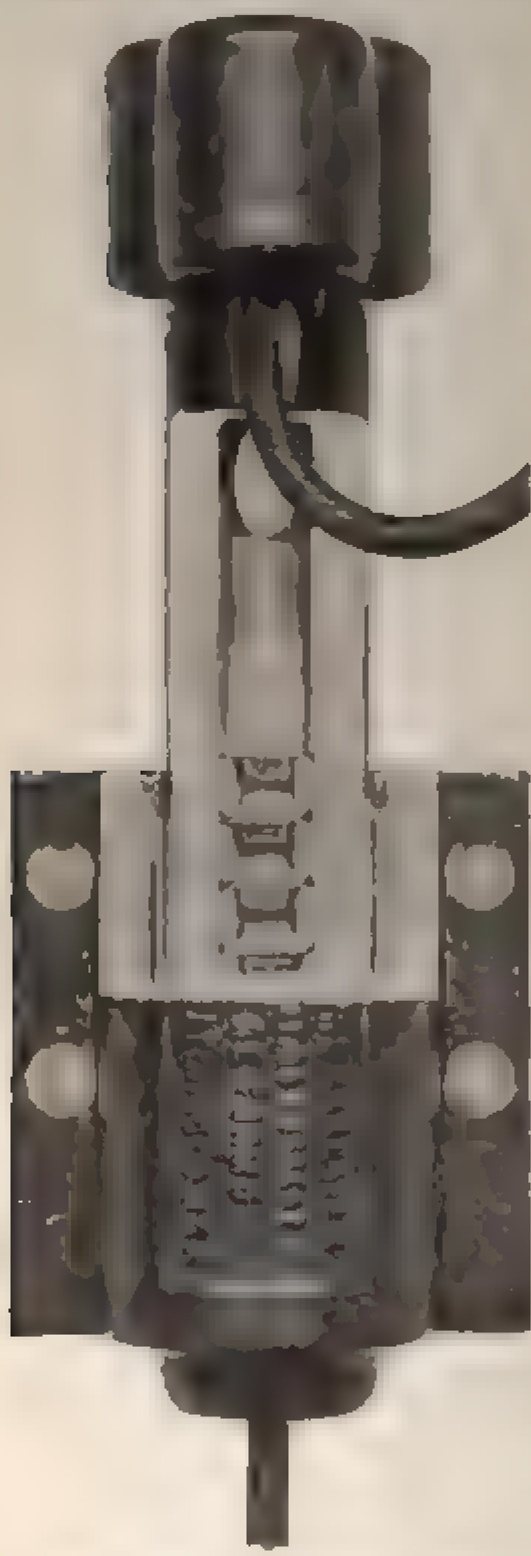


FIG 1140.—Sectional view of General Electric compression chamber lightning arrester for alternating-current circuits

The Oxide Film Lightning Arrester.—Lead peroxide has a specific resistance of about one ohm per cubic inch At a temperature of about 150° C, lead peroxide will be changed to red lead This has a specific resistance of about 24,000,000 ohms per cubic inch. If lead peroxide powder is placed between two electrodes and a current passed through it, the temperature due to the resistance where the peroxide comes in contact with

the metal will cause heat to be generated at the surface. When this heat reaches a temperature of 150° a film of a lower oxide of lead forms, producing a film of insulation which stops the current. A lightning arrester built on this principle consists of two sheet-metal electrodes about 8 inches in diameter separated by a porcelain ring about one-half inch thick. The discs are dipped in varnish, which covers them with a film just thick enough to withstand normal voltage. The space between the discs and the inside of the porcelain ring is filled with compressed peroxide of lead powder. At 300 volts per cell the varnish film prevents any appreciable current flowing. If the pressure rises, the film punctures in one or more minute points and a static discharge passes with perfect ease to earth. If, however, a generator current starts to follow, it must flow through the insulation at the minute points where the varnish was punctured. The current density at these points becomes very high. The heat generated speedily raises the temperature to a value sufficient to change the conducting peroxide in its path to non-conducting litharge. The film thus reseals and stops all further flow of generator current. The action is so rapid that it cannot be measured by an oscillograph capable of recording 2,000 cycles per second. That is, the action of the resealing apparently occurs in less than $\frac{1}{4000}$ of a second after the lightning discharge ceases. These arresters have recently proven highly successful on high-tension alternating-current systems.

The Vacuum Arrester.—The vacuum arrester consists of an hermetically sealed glass bulb with carbon electrodes mounted therein, these electrodes connecting with wires leading to the outside of the bulb, which is mounted on a porcelain block. The globe is exhausted to a high degree with the result that the resistance to the passage of static discharges is greatly reduced. It has been shown that $\frac{1}{8}$ inch air gap in a vacuum is equivalent to about $\frac{1}{1000}$ of an inch gap in the air. The ratio of conductivity is therefore about 125 for the vacuum to 1 for air. On this account it is possible to give the electrodes a very wide separation, thus entirely eliminating any chances of a ground being caused by lightning bridging the gap and burning the electrodes together. The arrester is especially adapted for fire-alarm systems and railway block signals, telephone lines, etc.

SECTION XXI CHAPTER II

STATION EQUIPMENT

LIGHTNING ARRESTERS

1. What is the object of the lightning arrester?

2. Explain the principle of the General Electric magnetic-blowout D. C. lightning arrester. Sketch.

3. Explain the principle of the Garton-Daniels D. C. lightning arrester. Sketch.

4. Explain the principle of the General Electric "shunted-gap" A. C. lightning arrester. For what kind of circuit is it particularly adapted? Sketch.

5. Explain the principle of the "aluminum cell" electrolytic lightning arrester. For what kind of circuits is it particularly adapted? Sketch.

6. Explain the principle of the "impulse-gap" A. C. lightning arrester. What are its advantages?

7. Explain the principle of the General Electric "compression chamber" lightning arrester. For what kind of circuits is it particularly adapted?

8. Explain the principle of the "oxide film" lightning arrester. What are its advantages?

9. Explain the principle of the "vacuum" lightning arrester. For what kind of circuits is it adapted? What are its advantages?

STATION EQUIPMENT

SWITCHBOARD APPARATUS

In power transmission systems it is desirable to know the voltage at the center of distribution rather than the voltage at the power station. Originally it was the custom to connect pressure wires at the center of distribution and lead them back to the power station to a voltmeter through which the voltage at the remote point could be known. In alternating-current systems it is unnecessary to use pressure wires. The voltage may be reduced at the station by an amount proportional to that

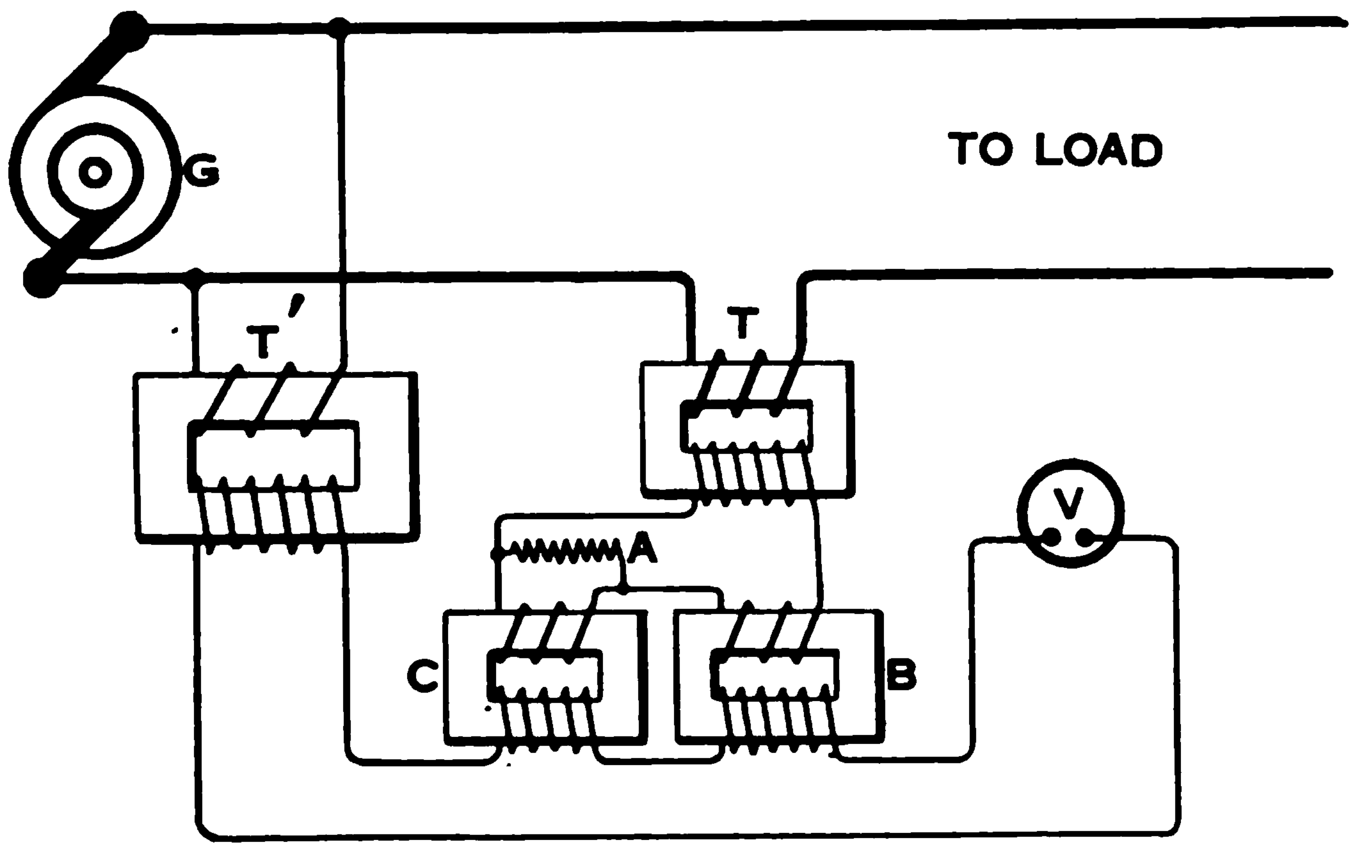


FIG. 1141.—Scheme of circuits for Mershon compensator.

lost in the line. The device for accomplishing this is sometimes designated a voltage compensator

Voltage Compensators.—The scheme of the compensator is illustrated in Fig. 1141. This consists of a transformer T', whose primary is connected to the source of supply and whose secondary is to furnish the potential for the voltmeter. In series with the load is the primary of a transformer T, the secondary being made to supply two auxiliary transformers B and C. Across the primary of C is connected a non-inductive resistance A. The drop across the secondary of this transformer will be

proportional to the resistance loss in the line. In the absence of any such resistance across the primary of transformer *B*, the drop will be proportional to the reactance of the line. The drop across the two in series will therefore be proportional to the impedance of the line. This voltage is made to oppose that delivered by the potential transformer *T'*. Therefore the voltmeter *V* receives a pressure which is that of the alternator minus the impedance drop in the line. In other words, it indicates the voltage at the load. This device **does not compensate** for the drop in potential as might be implied from the name, but

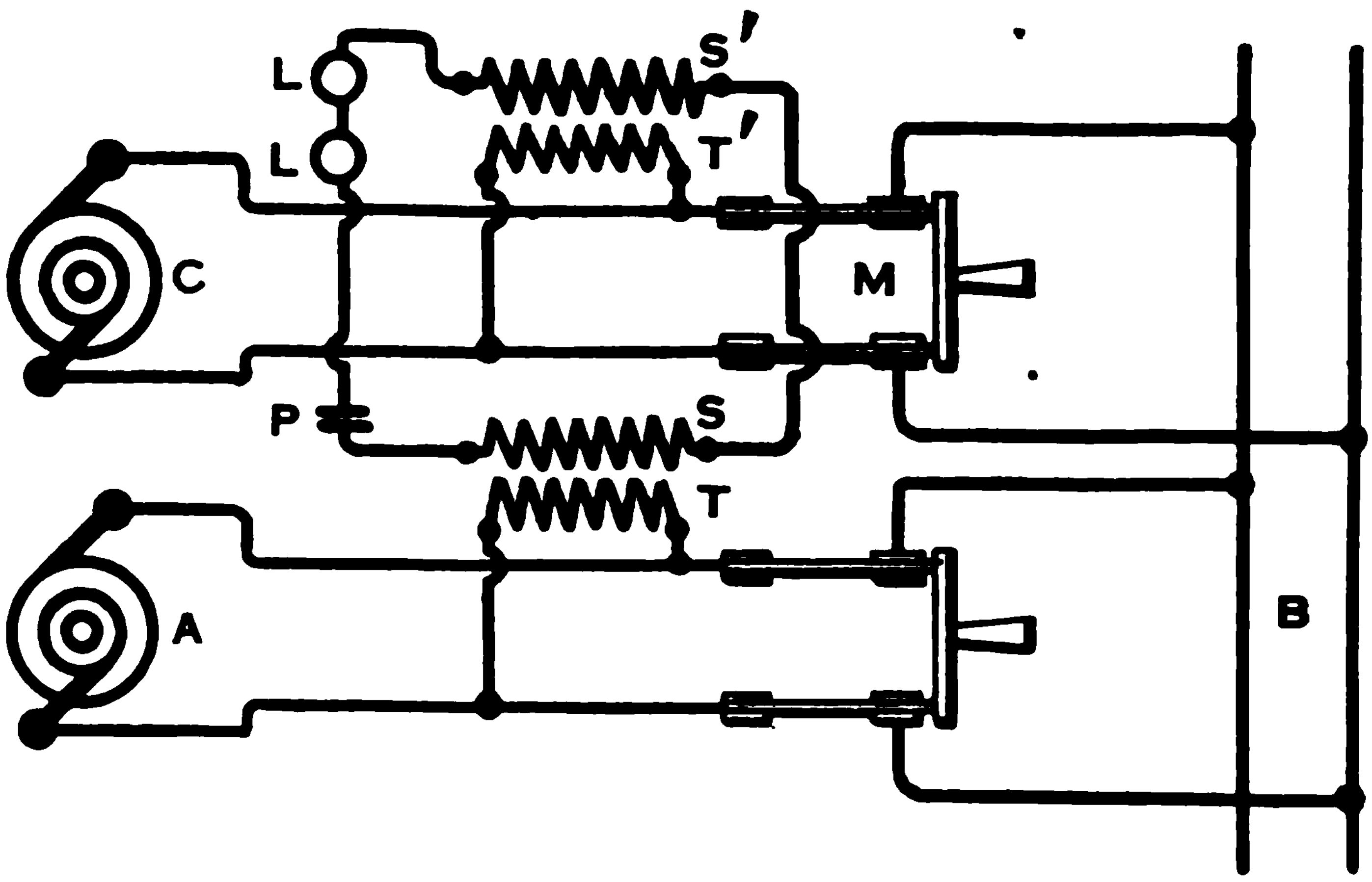


FIG. 1142.—Transformer connections for synchronizing two alternators.

simply subtracts the line loss from the generator voltage to give the proper indication on the voltmeter.

Synchronism Indicators

In order that alternators may be operated in parallel, three conditions must obtain:

First, they must be of the same e.m.f.

Second, they must be in phase.

Third, they must be in synchronism.

A simple diagram for synchronizing two alternators by means of lamps is shown in Fig. 1142. Here the alternator *A* is supplying the bus bars *B*, while the switch *M* is supposed to be open. If the alternator *C* is now brought up to speed and adjusted to proper voltage, the primaries of the synchronizing transformers

T and T' will be energized, the secondaries S and S' likewise energized, and the lamps L-L lighted in series when the switch P is closed. When the two machines are in proper phase alignment and the voltages are in opposition, the lamps will be dark. At the middle of a period of darkness the switch M may be closed and the machines thus placed in parallel.

The wiring of a low-voltage station for synchronizing a number of machines is shown in Fig. 1143. Here the main generator switch G of machine No. 1 is supposed to be closed, connecting it to the bus bars Two potential transformers, T and T', are used for synchronizing. One of these, T, has its primary permanently connected to the synchronizing bus bars, while the other, T',

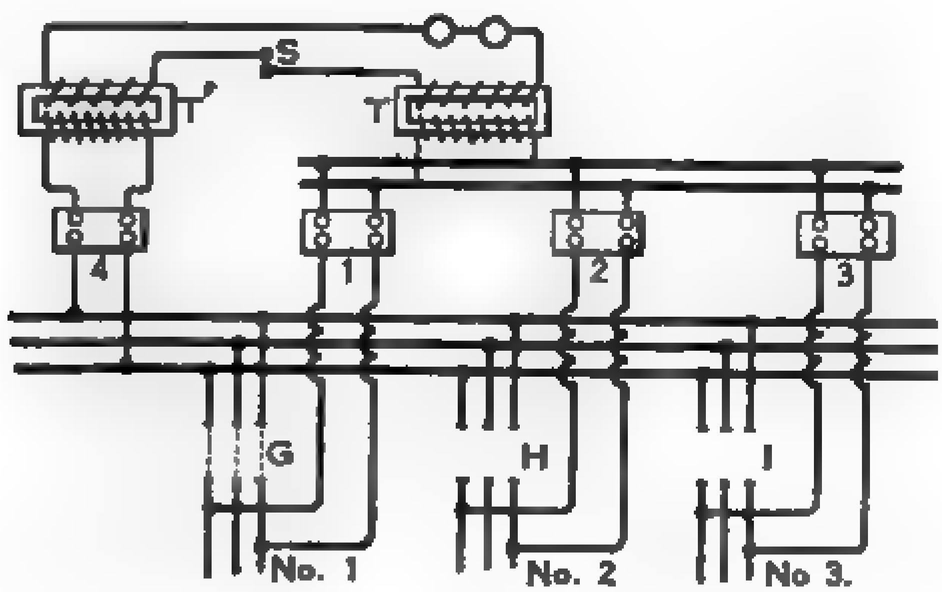


FIG. 1143.—Transformer connections for synchronizing any number of alternators.

has its primary connected to one phase of the station bus bars through a plug switch, 4. A four-point plug switch is provided by which the synchronizing bus bars may be plugged at the points 1, 2 or 3 upon any of the incoming machines before their main switches are closed. If it is desired to place machine No. 3 on the bus bars, the procedure is as follows. Machine No. 1 being in operation and the switch G closed, plug switch No. 4 also being closed, transformer T' is energized. A plug switch is now inserted in receptacle No. 3 which connects the synchronizing bus bars supplied by transformer T with machine No. 3. This machine is brought up to speed, its voltage is adjusted, and it supplies T with current. The secondaries of T and T' are now

energized by machines No. 3 and No. 1. As the speed of machine No. 3 is adjusted, the lamps fluctuate when switch *S* is closed. When the proper phase alignment is indicated the lamps will be dark and the main generator switch *I* for machine No. 3 may be closed, putting it in parallel with No. 1. The plug switch may now be removed from receptacle No. 3 and changed to receptacle No. 2 if it is desired to synchronize that or any other machine.

The ideal synchronism indicator should show three things:

First, the exact point of synchronism.

Second, whether the incoming machine is running too fast or too slow.

Third, the amount by which the incoming machine is fast or slow.

With lamp synchronizing, the first condition is shown approximately. Synchronism is indicated in the middle of a period of darkness. The second condition is not shown at all. The lamps fluctuate just as rapidly when the incoming machine is 10% too fast as when it is 10% too slow. The third condition is shown correctly. That is, the amount the incoming machine is fast or slow is shown by the rate at which the lamps fluctuate.

The Lincoln Synchronism Indicator.—Paul M. Lincoln designed a synchronism indicator which performs all three functions correctly. In its original form it was constructed from a fan motor frame with a laminated field structure. The arrangement is shown in Fig. 1144. Current from the bus bars or potential transformer supplied from the bus bars is introduced at the point *E*. This supplies the field coils *F-F* on the frame of the motor. Current from the incoming machine is fed in at the point *E'*. This current divides in two branches, the first through 1, leading through *L*, of high self-induction, thence through slip ring No. 3 to a coil *D*, placed on the armature. The other circuit, 2, leads through a non-inductive resistance *R* to slip ring 1 and thence through coil *C*. Both of these currents unite in a common return, passing through slip ring 2 to the other side of the circuit. The flux across the poles *A-A* lags 90° behind the voltage of *E* because of the self-induction of the winding *F*. The current in the coil *D* also lags 90° behind the e.m.f. *E'* because of the inductance of the coil *L*. It will be evident that, when the two sources *E* and *E'* are in phase, the current in *D*

will be in phase with flux across *A-A*. Torque will ensue, and the coil *D* will line up in the position shown with respect to the field poles *A-A*. Current passing into the coil *C* is in phase with the e.m.f. *E′*, because of the non-inductive resistance *R*. This current is therefore 90° ahead of the flux across *A-A* and cannot interact therewith to produce any torque. A pointer rigidly

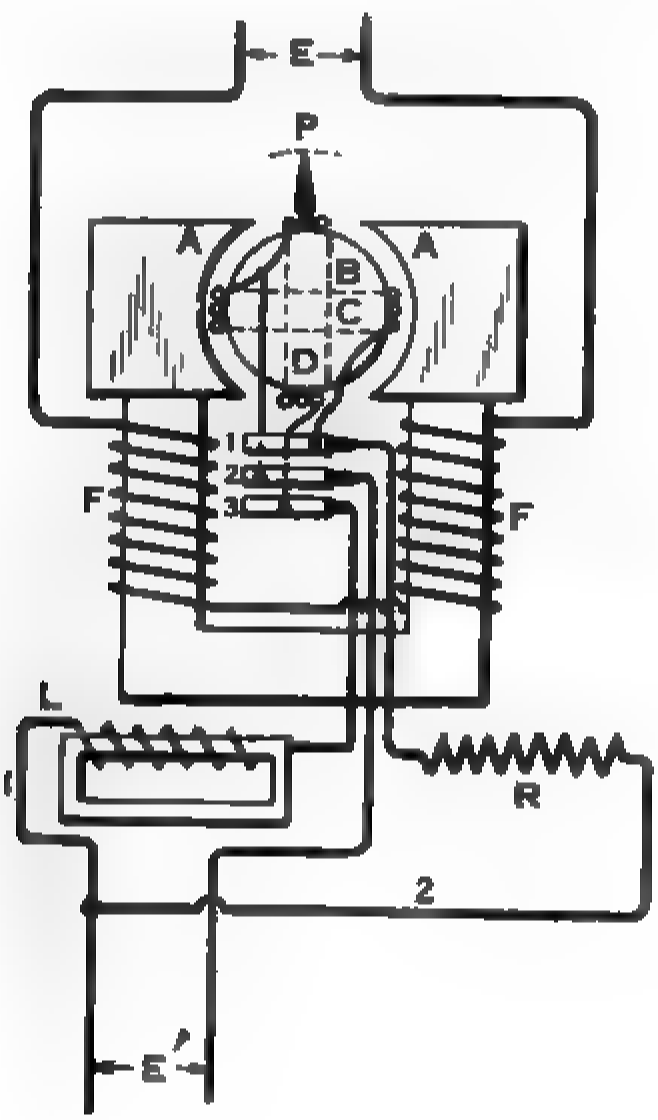


Fig. 1144.—Electrical circuits of Lincoln synchronism indicator.

attached to the shaft will, under these conditions, stand vertically upward. This indicates on a dial perfect phase alignment of the sources *E* and *E′*.

Should the incoming machine *E′* now slip back 90° in phase, the current in the coil *D* will likewise be retarded 90°. It will therefore cease to exert any torque with respect to *A*, but the current in coil *C* will now come into phase with the flux across *A-A* and it will rotate the armature and pointer 90° so that it

may include the flux A-A within its embrace. A change of phase of the source E' with respect to the source E is therefore accompanied by a mechanical change of 90° by the pointer. If E' is 45° behind E, the current in D is 45° ahead and the current in C is 45° behind the flux across A-A. The resultant flux of these two currents is 45° away from a horizontal line across A-A but is in time phase with the horizontal field flux from which it is displaced mechanically 45°. The pointer therefore rotates 45°. It must be evident that the pointer will assume

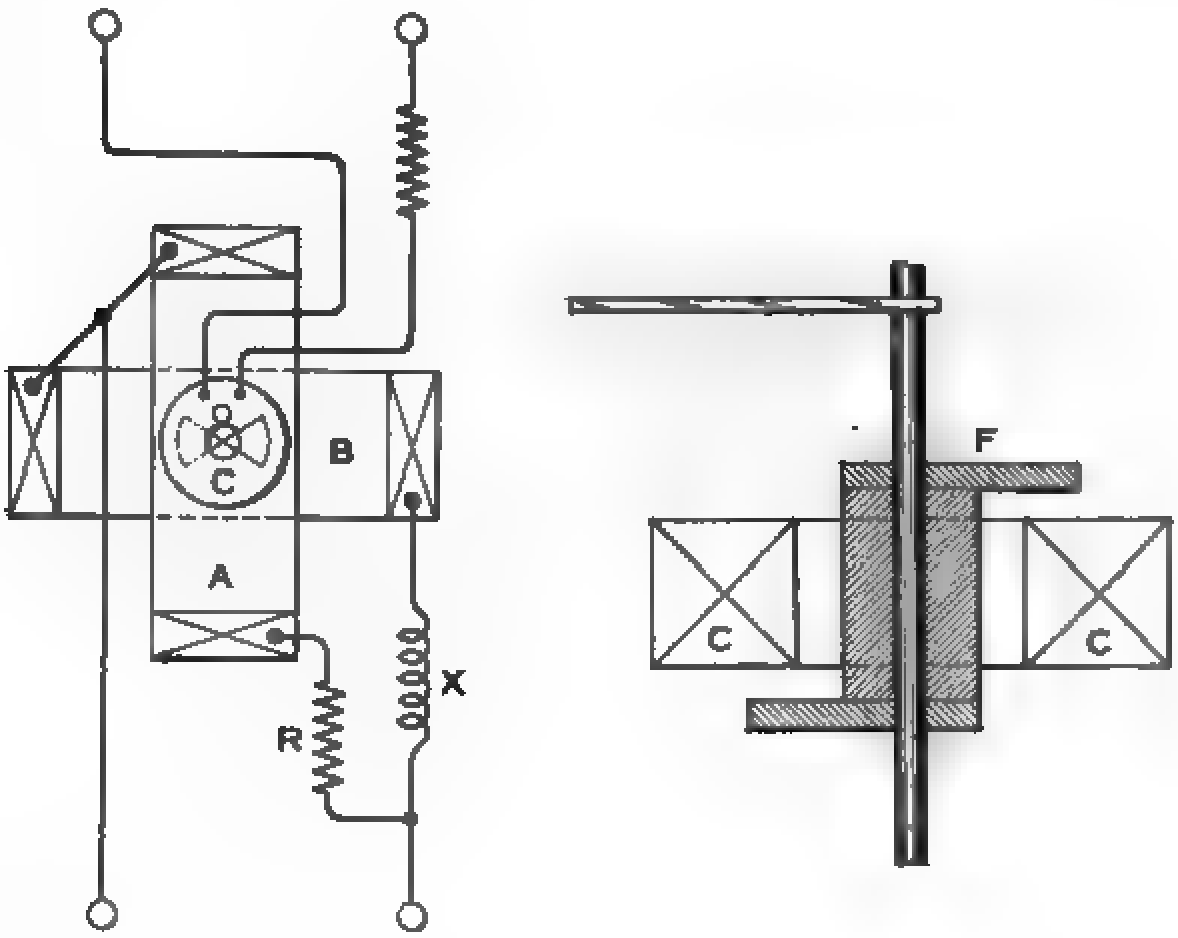


FIG. 1145.—Inductor type synchronism indicator.

at all times the same angle with the vertical that the phase relation of E' bears to E. If this angle is changing, as when the incoming machine is running at a different speed, the pointer will constantly change its position or rotate at a speed proportional to the difference of speed of the two machines.

The Inductor Type Synchronism Indicator.—Another type of synchronism indicator which has no moving coils or slip rings is shown in Fig 1145. In this instrument there are two coils A and B at right angles to each other. Coil A is connected across the bus bars through the resistance R, and coil B is connected

across the same bus bars through the reactance X. The fluxes produced by these coils will be displaced from each other by 90°. An inductor F is pivoted in the center of these coils and is magnetized by the coil C, which is connected across the incoming machine. When the machine is out of synchronism, the inductor will revolve with a speed depending on the extent to which the incoming machine differs in speed from the correct value. The direction of rotation will show whether it is fast or slow. When the machine is in synchronism but not in phase the inductor will remain stationary at that point of the cycle where the maximums of the two fluxes, the resultant of A-B and that from C, coincide. When the machine is in phase, the indicator will hold the pointer in a vertical position. This type is com-

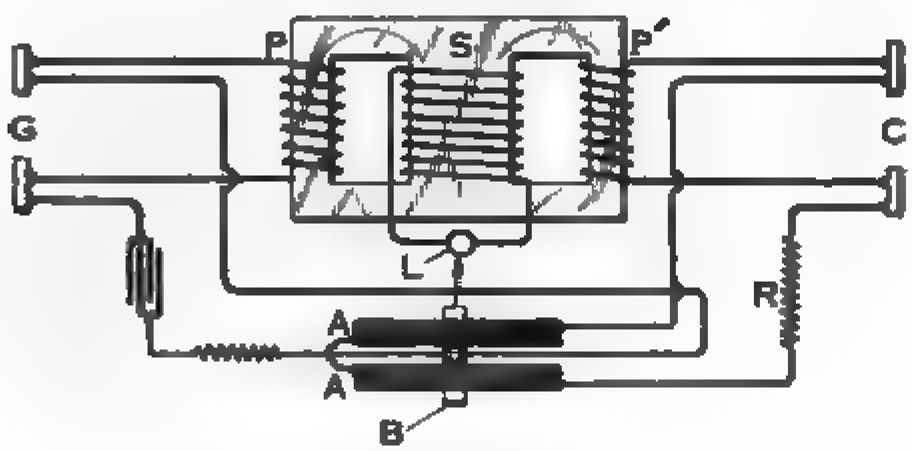


FIG. 1146.—Electrical circuits of Weston oscillating synchroscope.

monly used for synchronism indicators of small size. It does not have sufficient torque to operate the larger diameter meters.

The Weston Synchronism Indicator.—In 1911 the Weston Company produced a new type of dynamometer which was applied to three lines of instruments: wattmeters, synchroscopes, and power factor meters.

The Weston synchroscope differs from the Lincoln synchroscope in that it is of the oscillating instead of the rotating type. It contains a pointer mounted behind a translucent glass screen which is lighted by a lamp connected to a transformer to synchronize light. Fig. 1146 shows the diagram of connections. This includes a synchronizing transformer having two primary windings, one, P, energized by the incoming machine G, the other, P', energized by the bus bars C. When the two sources are in the proper phase, the fluxes from P and P' combine and flow through the secondary S, and the lamp L is lighted. The

movement consists of two coils, one, A-A, which is stationary; the other, B, which is movable. A-A is connected to the bus bars in series with a non-inductive resistance R. The current in this coil is in phase with the voltage. B is mounted in jeweled bearings and is maintained in a vertical position by means of spiral springs through which current is introduced from the incoming machine G in series with a condenser J. The current in the coil B is thus 90° ahead of the e.m.f. When the two sources are in phase, the movable coil will have a current 90° out of phase with the stationary coil and no torque will be developed between them. The springs therefore hold the movable coil vertically. At the same time the lamp is lighted bright, and a shadow of the pointer is thrown by this lamp upon the translucent screen in front. Should the incoming machine drop back 180° in phase, the current in the coil B will be 90° behind A instead of 90° ahead. There will again be no torque between these two coils, and the index will remain vertical. The lamp L, however, will now be extinguished because of the phase relation of the primary currents in the transformer, so that the pointer will not be seen on the glass dial. Thus the instrument distinguishes between the proper phase alignment and the exact opposition of phases by causing the pointer to appear when the phases are right and disappear when the phases are wrong. Should the incoming machine lag 90°, the current in the coil B falls into phase with the current in the coil A. Torque now ensues, and B tends to move to the left 90°. If the incoming machine is constantly changing its phase position, the needle changes its position also and is accompanied by pulsations of the lamp. When the phase relation gets beyond a certain point the torque reverses and the needle moves to the other side of the scale. It moves forward, however, during the period when the lamp is light and returns when the lamp is dark. The effect upon the eye, therefore, is as though the needle actually rotated instead of oscillated. This instrument has the advantage of jeweled supports for the moving parts and the absence of sliding connections between the moving coil and the external circuit.

Power-Factor Indicators

A power factor indicator does not indicate a quantity but an angle, therefore it requires no force of control.

The Weston Power-Factor Indicator.—The circuits of the Weston power-factor indicator are shown in Fig. 1147. Its principle is similar to that of the Lincoln synchroscope. The source of supply is connected to *D-E* and the load to *F-G*. The instrument contains a stationary coil *C*, in series with the load. The moving system consists of two coils *A* and *B*, permanently fixed at right angles to each other and mounted in jeweled bearings so that they may turn through an angle. Coil *B* is in series with a non-inductive resistance *R*. Coil *A* is in series with an inductive reactance *L*. Current is led into and out from these coils through three fine wire spirals which exert no torsion whatever. In the absence of the application of current or e.m.f. the needle may stand in any position, for there is no force of

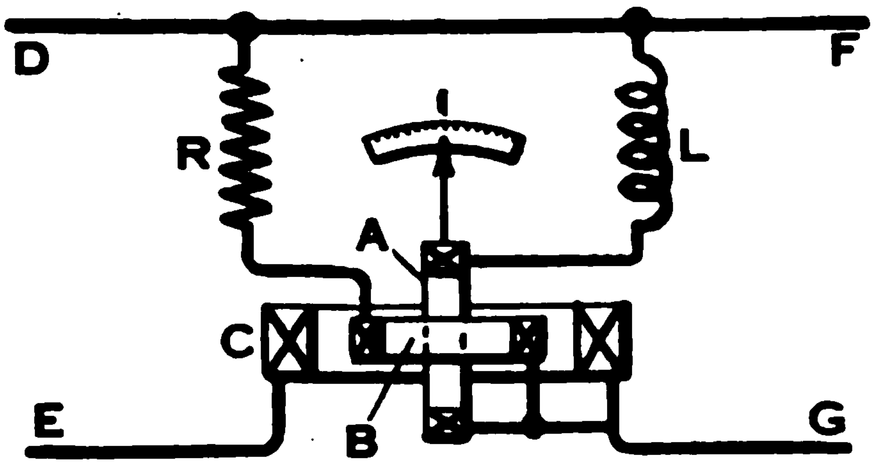


FIG. 1147.—Electrical circuits of Weston power-factor indicator.

control. When the current in the line, and therefore the current in *C*, is in phase with the e.m.f., the current in *B*, being in series with a non-inductive resistance, is likewise in phase with the e.m.f. *B* and *C* then develop torque with respect to each other and line up. This holds the index at the center of the scale, indicating 100% power factor. At this time the current in *A*, lagging 90° through the self-induction of *L*, exerts no torque with respect to *C* and therefore has no influence upon the position of the pointer. Now, should the current in the line lag 45° or any other number of degrees, this phase displacement in *C* will interact with the resultant of two currents in *A* and *B*. The moving member *A-B* will therefore turn to express by a resultant position, the angular relation of the line current and e.m.f. It will be remembered in the Lincoln synchroscope in Fig. 1144 that the position of the needle at any instant expressed the phase angle at that moment between the voltages of the two sources. In Fig. 1147 the same

result is produced except that the phase angle between the load current and the line potential is shown.

The Westinghouse Induction-Type Power-Factor Indicator.—Another type of power factor indicator which is widely used consists of three current coils spaced 60° apart and producing a rotating field. For two-phase work there are two coils spaced 90° and for single-phase operation a phase-splitting device is employed, the object in any case being to produce a rotating field. In the center of the frame supporting these current coils, which are placed somewhat similar to the coils in an induction motor, is a magnetic vane which is magnetized by a voltage coil connected across one phase. The pointer will take up a position in the rotating field depending on the phase relation between the current producing this field and the current in the voltage coil.

There are no current-carrying parts in the moving element, and the movement is magnetically damped by drag magnets operating on an aluminum disc. No control springs are required. The movement is capable of rotating 360°, the upper half of the scale reading lag or lead, and the lower half being used for reversed power. Polyphase indicators are adjusted to frequencies from 25 to 60 cycles for the same meter.

Frequency Indicators

The Weston Frequency Indicators.—Frequency indicators like power factor indicators do not indicate a definite quantity and therefore require no force of control. The Weston frequency meter contains no springs or control. It consists of two coils connected in series across the line with reactance in series with one and resistance in series with the other. The circuits are shown in Fig. 1184. The coils are placed at right angles to each other, and the magnetic effect of the two is jointly brought to bear upon a pivoted soft iron needle placed at the center of the two coils from which an index extends upward to the scale. Coil 1-1 and a reactor X_1 are placed in series, and a resistor R_1 is placed in shunt with both. Coil 2-2, and a resistor R_2 are placed in series, and a reactor X_2 is placed in shunt with both. The whole combination resembles a Wheatstone Bridge, balanced at normal frequencies and connected in series with another reactor X, to damp out the higher harmonics. The theoretical arrangement is shown in Fig. 1149. An increase of frequency

increases the reactance of X_1 and X_2, and upsets the balance of the bridge. This diminishes the current through coil No. 1, and increases the current through coil No. 2. The resultant flux, instead of being midway between the two coils as normally, is now overpowered by coil No. 2, and the soft iron needle moved over and the index swings to the left.

The Frahm Type of Frequency Indicator.—While the types just described are generally used in this country for switchboard instruments, the vibration type of frequency indicator is very popular for portable use and is used to a lesser extent on switchboards. It usually consists of an electro-magnet, the coil of which is connected to the circuit under consideration. The

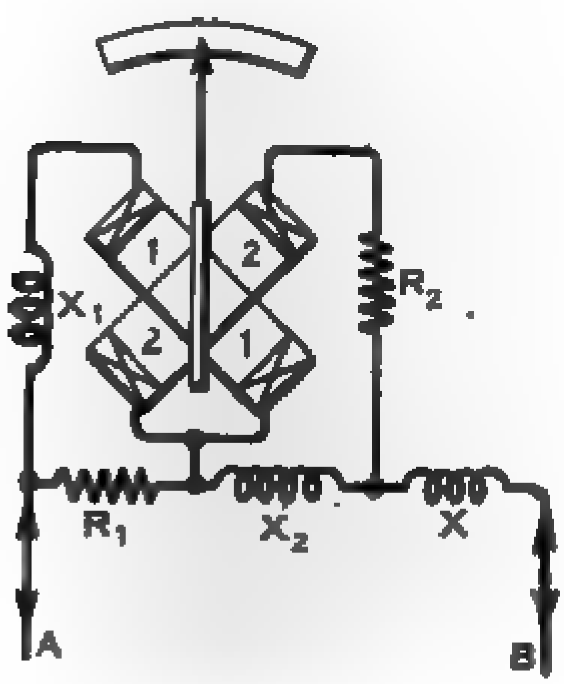


FIG. 1148.—Electrical circuits of Weston frequency meter.

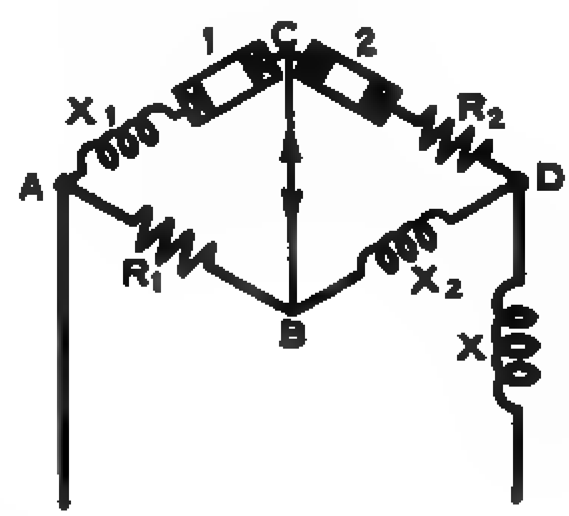


FIG. 1149.—Wheatstone Bridge principle in Weston frequency indicator.

frequency of the flux in the core of this magnet is, of course, that of the supply. In front of this magnet and a short distance away are mounted thin strips of steel each having a definite natural period of vibration The period of each strip or reed depends upon its length and its mass. By adjusting either or both of these so that the natural period of each reed is one-half cycle removed from that of the reed next adjacent, a considerable range is obtained with a reasonable degree of accuracy When current is admitted to the coil of the magnet, the flux produced crosses these reeds, and the one having the same period as the flux, vibrates, thus indicating the frequency of the line. Usually more than one reed will vibrate, but the one having the greatest

amplitude indicates the correct value. Fig 1150 shows such an instrument manufactured by Hartmann and Braun. The appearance of the ends of the reeds, bent over and painted white

Fig. 1150.—Hartmann & Braun frequency indicator

so as to be conspicuous, is shown in this illustration. These instruments are made with two ranges, the change from one to the other being made by a small knob at the side of the meter

SECTION XXI CHAPTER III

STATION EQUIPMENT

SWITCHBOARD APPARATUS

1. Explain the general plan of the Mershon voltage compensator.

2. What conditions must obtain in order that two alternators may be operated in parallel?

3. Explain in detail the method of synchronizing two alternators by means of lamps. Sketch circuits.

4. What three conditions must be shown by an ideal synchronism indicator?

5. To what extent do lamps for synchronizing purposes fulfill these requirements? Wherein do they fail?

6. Explain the principle and construction of the Lincoln synchronism indicator. Sketch.

7. Explain the inductor type of synchronism indicator. Sketch.

8. Explain the principle and construction of the Weston oscillating synchroscope. Sketch.

9. Explain the principle and construction of the Weston power factor indicator. Sketch.

10. Explain the principle and construction of the Westinghouse induction type of power factor indicator.

11. Explain the principle and construction of the Weston frequency meter. Sketch.

12. Explain the Frahm type of frequency meter. Sketch.

STATION EQUIPMENT

INDUCTION WATT-HOUR METERS

All induction watt-hour meters employ an induction motor as the propelling force.

The Shallenberger Ampere-Hour Meter.—One of the earliest induction-motor meters was simply an ampere-hour meter. This was designed by Oliver P. Shallenberger. Current from the source P passes through a stationary series current coil A-B, Fig. 1151, divided into two parts to allow the shaft of the meter to pass through. Within this coil is a bare, short-circuited coil C, of one convolution of copper. This coil is placed at an angle of 45°, approximately, with respect to the main coil.

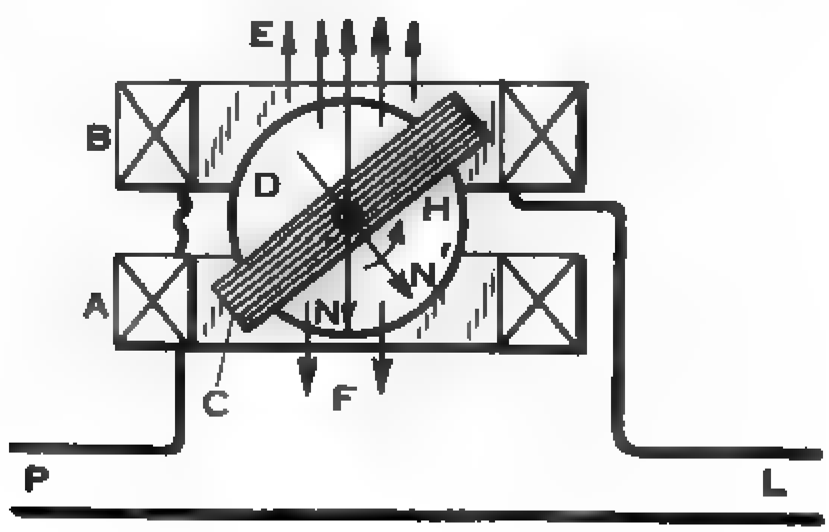


FIG. 1151.—Principle of Shallenberger alternating induction-type ampere-hour meter.

Within this coil mounted upon a shaft is an aluminum disc D When an alternating current flows through A-B it produces an alternating flux which simultaneously induces secondary currents in C and D. While these currents rise and fall in time phase, the magnetic fluxes produced thereby are at an angular displacement with respect to each other and therefore interact to produce torque. Thus, if at a given instant the primary flux is in the direction E, the reaction of the secondary currents in the disc will tend to produce flux in the direction F. At the same time the induced current in C rises, but tends to produce a flux perpendicular to the plane of the coil or in the direction N'.

These fluxes tend to line up, hence the disc moves in the direction of the arrow *H*. These impulses are repeated with each alternation, or, at 60 cycles, 120 times per second. The torque between the disc and the coil *C* may be varied by altering the angular position of the coil *C*.

Principles of Induction Watt-Hour Meters.—In all induction watt-hour meters there are at least two coils, one a potential

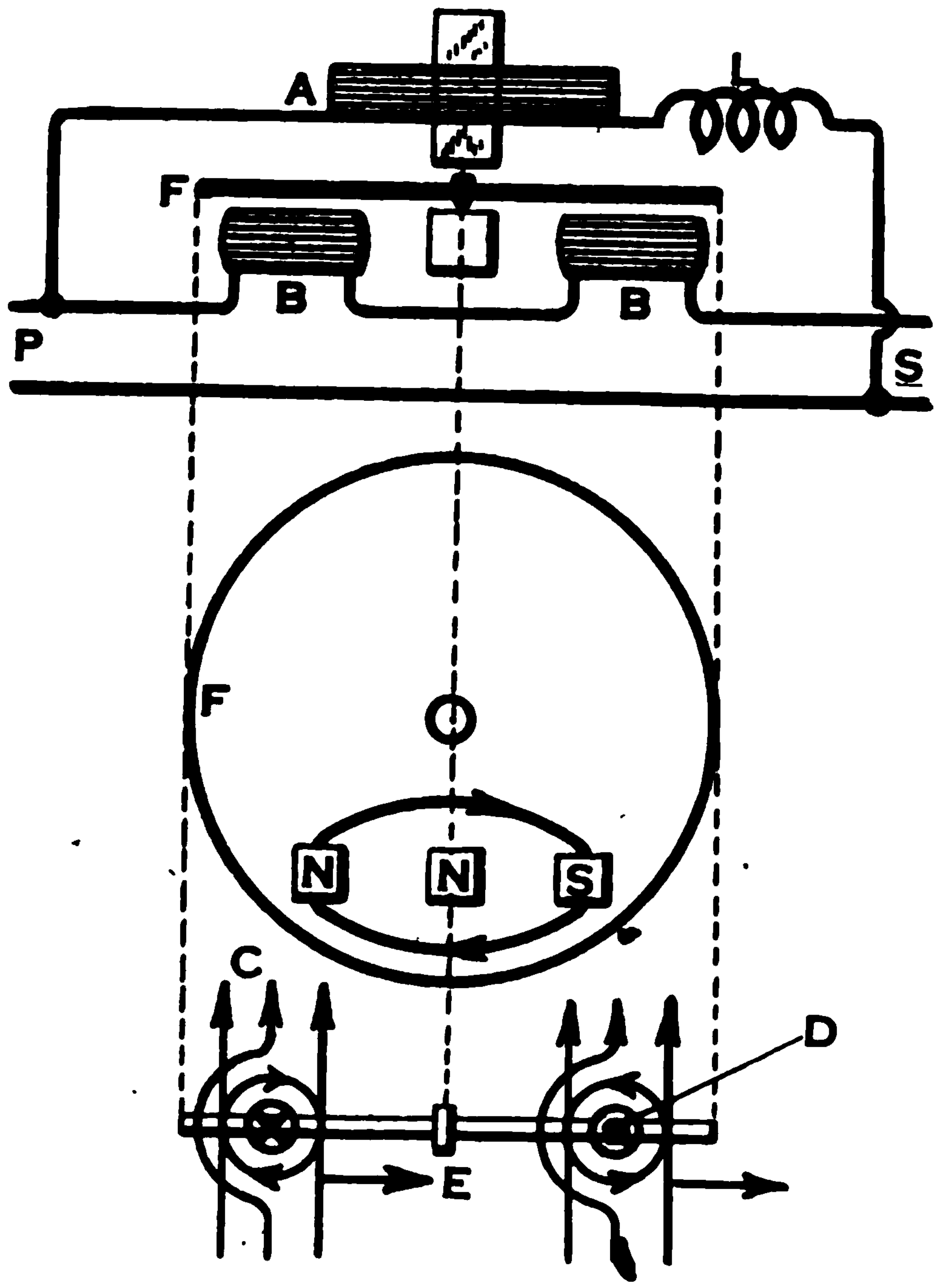


FIG. 1152.—Principle of General-Electric alternating current induction-type watt-hour meter.

coil, *A*, Fig. 1152, connected across the line with an inductance *L* in series therewith. In this circuit the current represented by curve *B*, Fig. 1153, lags 90° behind the line e.m.f. represented by curve *A*. This current produces a flux in phase with it. This flux produces eddy currents in the disc by induction. These currents, which are 90° behind the flux, are represented by the curve *C*. Next there are two series coils *B*-*B*, Fig. 1152, in series with the load. These are often constructed without iron

cores, for this circuit must be noninductive. The fluxes due to this series current are in phase with it. Therefore the eddy currents induced in the disc by the voltage coil in shunt with the

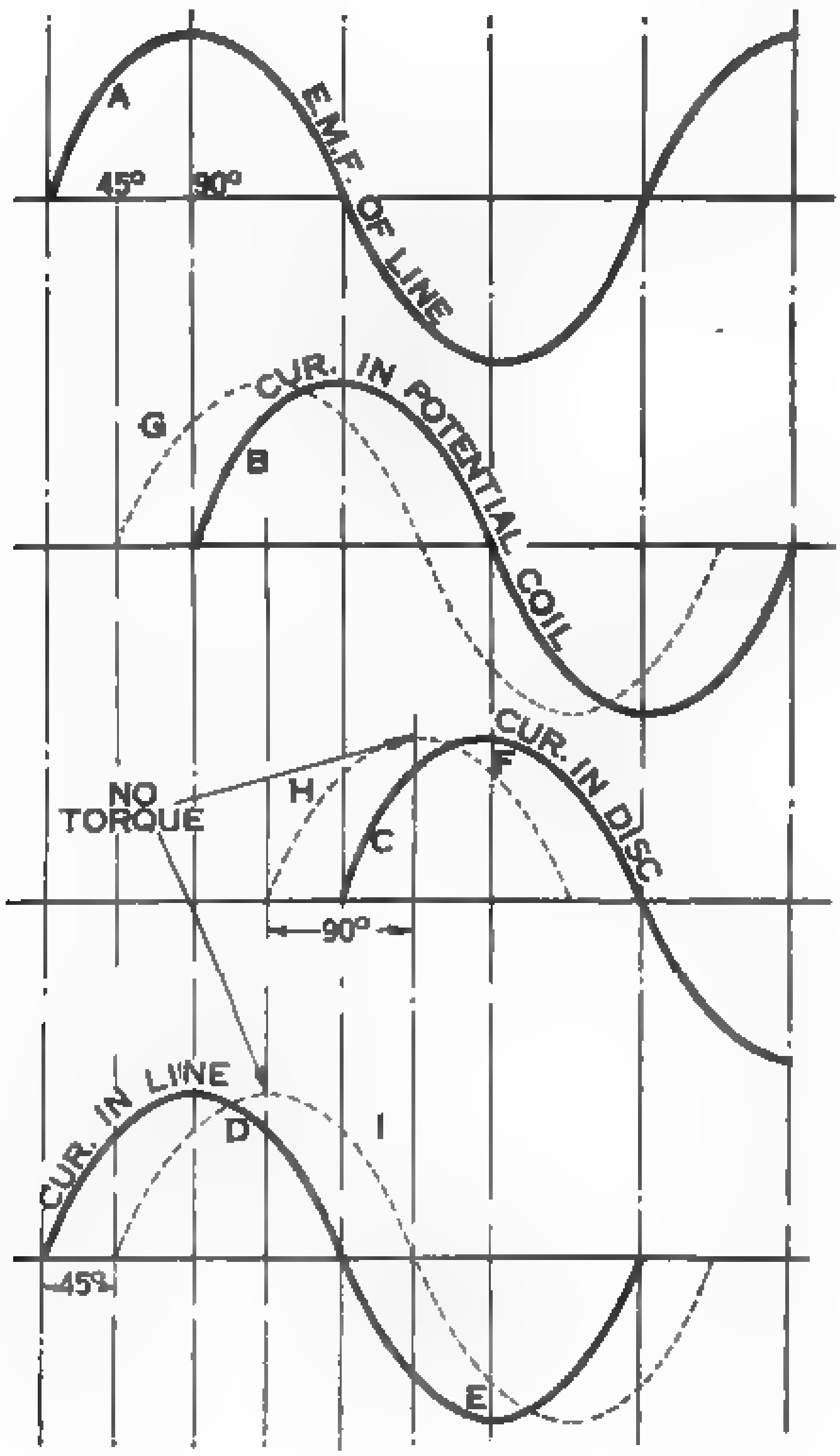


FIG. 1153.

line, and the fluxes due to the current coils in series with the line, reach their maximum value at the same time at unity power factor and interact to produce torque. The amount of torque depends upon the relative values of voltage and current

in the main line. The relation between these currents and voltages may be seen from Fig. 1153. Here curve *A* represents the e.m.f. of the line. Curve *B* represents the current in the potential coil made to lag by self-induction 90° behind the e.m.f. of the potential coil. Curve *D* shows the current in the main line which, at 100% power factor, is in phase with the e.m.f. *A*. As the current curve reaches its maximum at the point *E* at the same time that the induced currents in the disc reach their maximum at the point *F* they interact to produce torque, even though in the figure they are in opposite directions.

Now it is necessary that the current in the voltage coil, and therefore the flux produced by it, shall be exactly 90° behind the e.m.f. of the line. If this is not the case, the meter will register accurately only at 100% power factor, and, as the power factor departs from 100%, the meter registers more and more inaccurately. Thus, if the current and flux in the potential coil lagged only 45° behind the line e.m.f., and the power factor of the system fell to 70.7%, indicating an angle of lag of the load current of 45°, the torque between the two elements of the meter would be nil and the meter would register zero. This may be understood by referring again to Fig. 1153. Here the dotted curve *G* pictures the case where a lag of 45° occurs with regard to the current and flux in the potential coil instead of 90°. The resulting current induced in the disc would now be in the position *H* instead of *C*. With a lag of the load current of 45°, as represented by the curve *I*, it will be evident that the curve *H* and the curve *I*, upon which the meter depends for the development of torque, will be displaced from each other exactly 90°. Therefore it is obvious that no torque will be produced.

Lagging of Watt-Hour Meters.—There are several possible methods of making the current and resulting flux due to the potential circuit lag exactly 90° behind the impressed e.m.f. When this is accomplished the meter registers accurately at all power factors.

The reason that the angle is not exactly 90° naturally is that the voltage coil possesses resistance as well as inductance. The hysteresis and eddy current losses in the core will also be inevitable. Both of these tend to lessen the angle of displacement.

The adjustment by which the exact quadrature relation between the potential circuit flux and the line e.m.f. is accom-

plished is called "lagging" the meter—that is, compensating the meter for inductive as well as non-inductive loads. Auxiliary

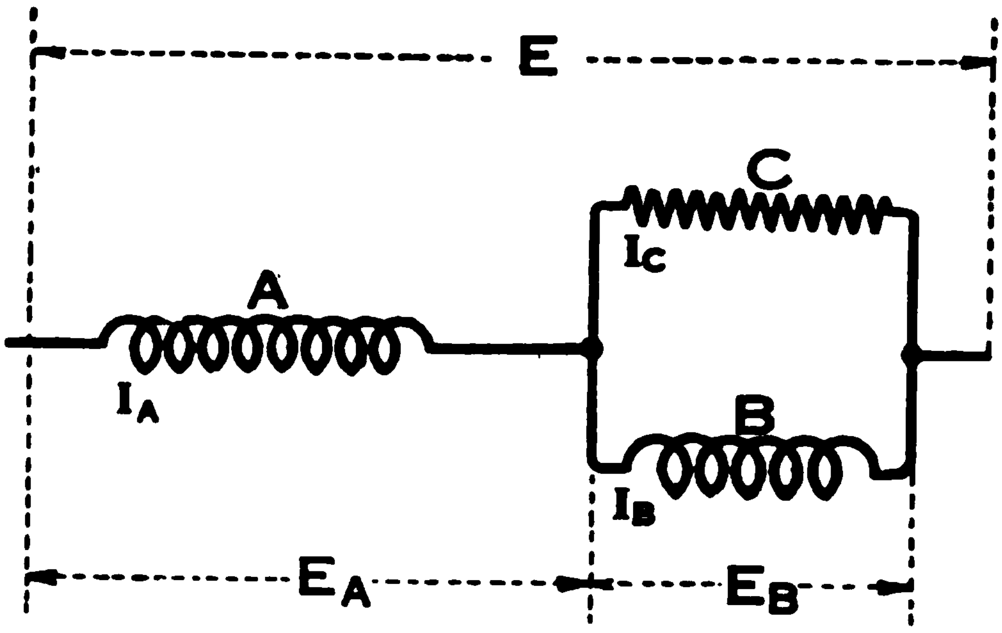


FIG. 1154.

coils are employed to produce the exact quarter-phasing of the flux due to the voltage and current coils. These auxiliary coils are connected in the potential circuit. One method of bringing

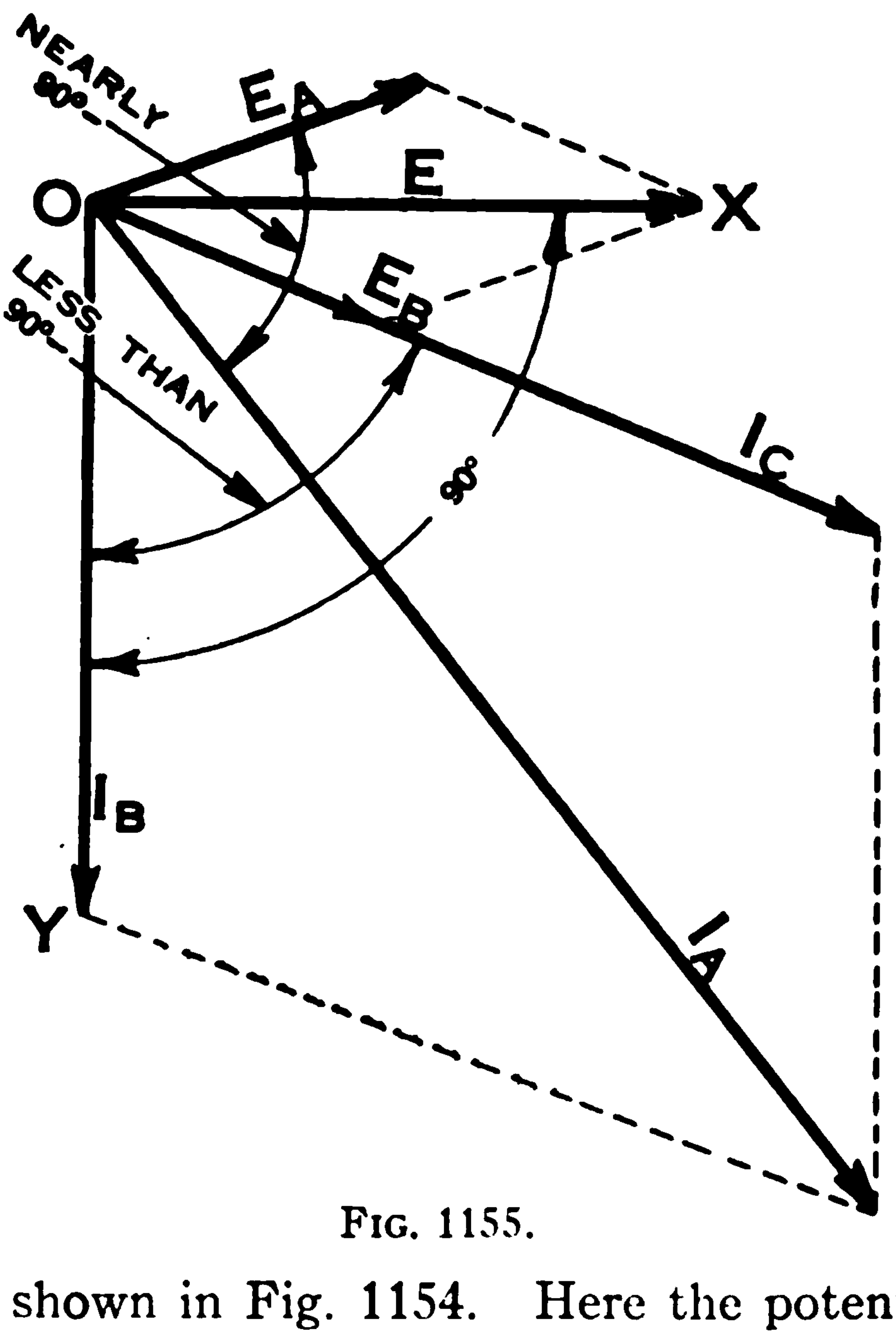


FIG. 1155.

this about is shown in Fig. 1154. Here the potential circuit is electrically divided into three parts: A, highly inductive; B, less inductive, and C, entirely non-inductive. B is the coil

which is responsible for the actuating flux. The line voltage E is laid off in Fig 1155, in the direction O-X This is split up into two components, Ea, which is the drop across A, and Eb, which is the drop across B and C. The current flowing through this circuit is Ia. After passing through A this is split into two parts, one portion of which, Ic, goes through C; the other, Ib, through B Now the resistance of A prevents Ia from lagging exactly 90° behind Ea The current Ic in C will be in phase with the voltage of Eb across it, which is also the voltage impressed on B. The current in B, which is O-Y, will also be less

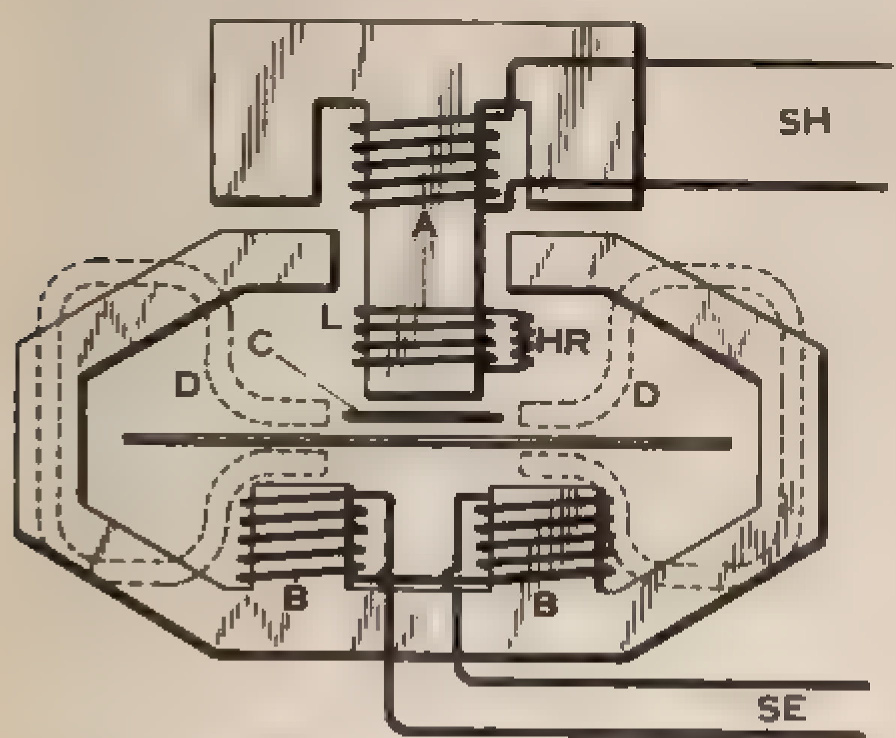


FIG. 1156—Electrical and magnetic circuits of late type of General Electric induction watt-hour meter.

than 90° behind Eb, because of the resistance of B. The phase relation, however, of the current O-Y in B, can be made anything desired with reference to the line voltage O-X, by varying the reactance of A Thus if A's reactance is increased, the current Ia, in turn, will lag more This will make the current Ib lag more Thus, by altering the reactance of A, the phase direction of Ib can be adjusted to 90° exactly or even made more or less at will.

The simplest and most commonly used method of lagging a meter consists in winding upon the core of the voltage coil or interposing in the path of the voltage flux a short-circuited coil of adjustable resistance. This acts as the secondary of a trans-

former with the voltage coil as the primary. Such a coil is shown at *L*, in Fig. 1156, which represents a General Electric meter. This principle is used for lagging the General Electric, Westinghouse and Sangamo meters.

The reaction of this coil on the flux due to the potential coil produces the proper quarter-phase relation between the e.m.f. on the voltage coil and the resulting flux.

An explanation of the reason why the addition of such a coil produces the required 90° angle of lag may be seen by reference to Fig. 1157. If *O-L* represents the voltage applied to the shunt coil and *O-C* represents the current in these coils, the angle *L-O-C* shows the phase relation between them. This angle is slightly less than 90°, due to the copper and core losses in the shunt system. *O-S* represents the voltage induced in the short- circuited coil *L*, Fig. 1156. The current in this coil is in phase with the voltage, as there is practically no leakage flux around this coil itself and thus practically no reactance in that circuit and may be represented by the line *O-D*. The current *O-C* and the current *O-D* have a combined magnetizing effect on the iron core which corresponds in effect to the resultant of *O-C* and *O-D*, which is *O-X*. *O-X* is evidently 90° from *O-L*. Since the resistance of the circuit of the short-circuited coil may be changed as desired and the current *O-D* will be correspondingly changed, it is evident that the angle *X-O-L* may be made anything desired within reason. This compensation is accurate only at the frequency for which adjustment is made.

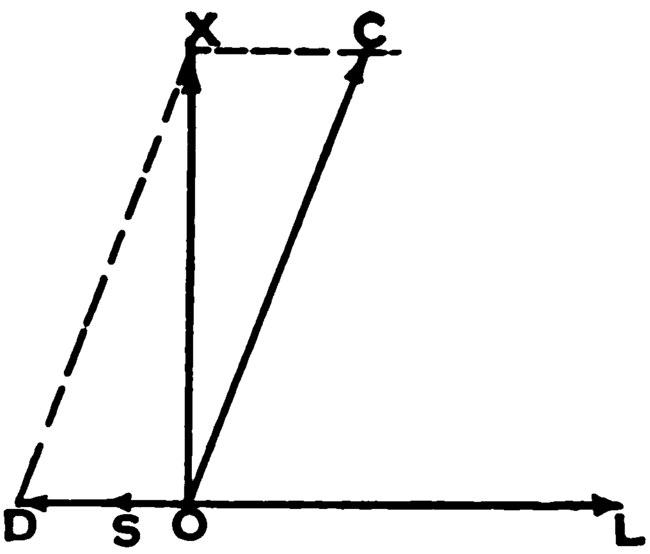


FIG. 1157.

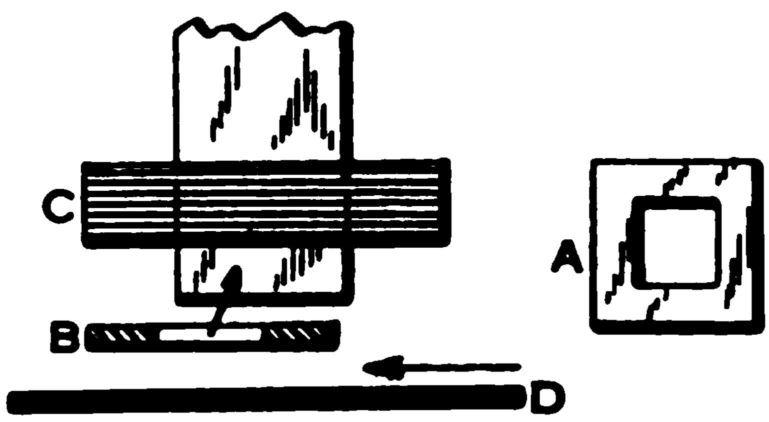


FIG. 1158.

Only part of the flux due to the voltage coil, *A*, Fig. 1156, passes through the lag coil. The resistance of the lag coil is adjusted by an external resistance *H-R*, until the phase displacement of the resultant flux is exactly 90° in time phase behind the flux due to the series coils *B-B*.

Light Load Compensation.—The principle of light load compensation is similar in all induction motor meters. The device operates so that at any instant the flux distribution over the pole face of the core of the voltage coil is not uniform. This variation in the distribution of the magnetic flux produces the effect of a rotating field. It resembles, in principle, the shading coil motor. In some meters this takes the form of a clip, *A*, Fig. 1158, which is placed in the position *B*, so that a portion of the flux due to the potential coil, *C*, passes through it. The result is to produce a rotating field with respect to the disc *D* and the potential coil pole, even though there be no current whatever in the series coil. By shifting this clip more or less across the pole face, the resulting torque and consequently the speed at light load may be altered at will. This clip is shown at *C* in Fig. 1156.

Sometimes the two opposite poles of the magnetic circuit of the potential coil on the upper and lower faces of the rotating

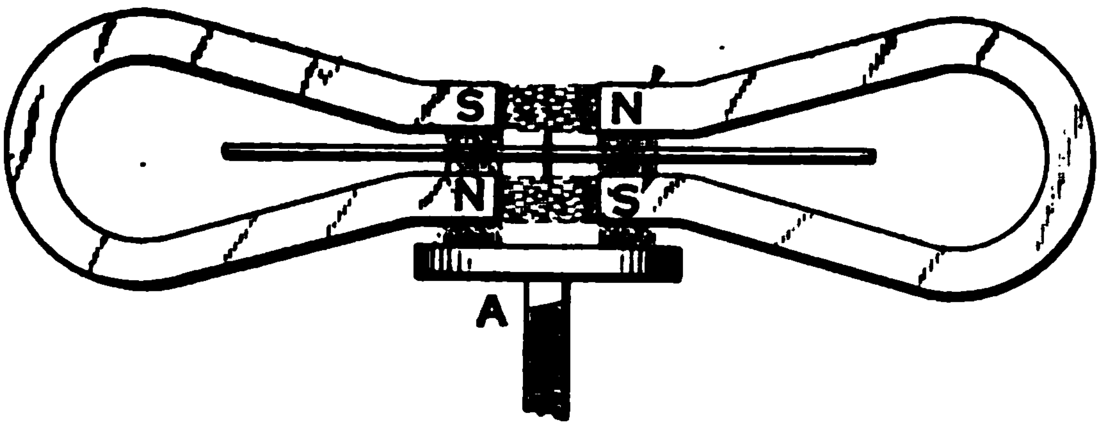


FIG. 1159.—Astatic arrangement of drag magnets in watt-hour meter.

disc are shifted with respect to each other in order to produce this light load adjustment. Sometimes pole shoes are provided which may be raised or lowered with respect to the disc, and thus a modification of the flux distribution is brought about. Any method by which this result is accomplished will suffice.

Full Load Compensation.—The full load adjustment of these meters is accomplished by varying the retarding effect of permanent magnets in three ways:

First, by shifting the position of the drag magnets with respect to the circumference of the disc. This is the plan in Fig. 1131. If the magnets *D-D* are moved toward the circumference the retardation is greater, if toward the center it is less.

Second, by shunting some of the magnetism around the disc as in Fig. 1159. Here what is called an astatic arrangement of

the magnets is employed, so that the flux may pass either from N to S and from N' to S', across the disc, or it may pass from N to S', and thence around through the magnets and from N' to S, avoiding the disc. The adjustment consists of a soft iron screw, A, which may be raised or lowered. When it is raised, it provides a path from N to S', via the screw, and diverts some of the flux which previously passed through the disc around it. The retardation is therefore reduced and the meter speeds up.

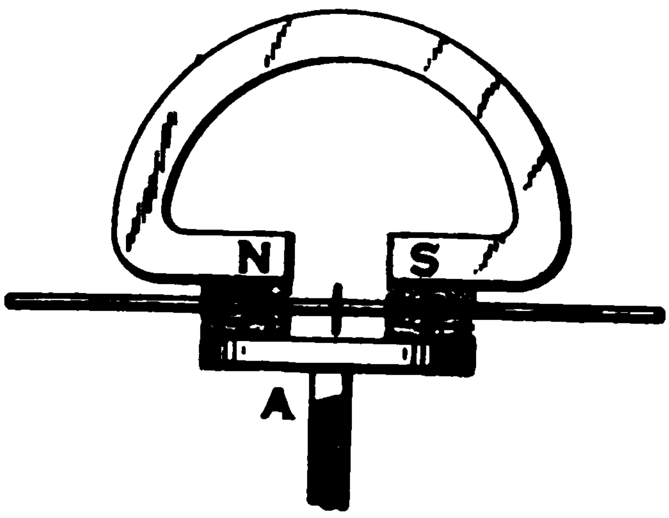


FIG. 1160.—Varying reluctance of magnetic circuit of drag magnets.

Third, by varying the length and reluctance of the air gap in the magnetic circuit. This plan is shown in Fig. 1160. Here a screw A is raised or lowered, thereby varying the air gap by which the flux passes from the north pole of the permanent magnet down through the disc and thence across the screw head and back up through the disc to S. In this case raising the screw increases the flux through the disc and increases the retardation, slowing the meter down.

SECTION XXI CHAPTER IV

STATION EQUIPMENT

INDUCTION WATT-HOUR METERS

1. Explain the construction and principle of operation of the Shallenberger ampere-hour meter. Sketch.

2. Explain the construction and principle of operation of the General Electric induction watt-hour meter. Sketch.

3. Why must the current in the voltage coil and the flux produced by it be displaced exactly 90 degrees in phase from the e.m.f. of the line? How is this brought about?

4. What is meant by "lagging" a meter?

5. Explain how three coils possessing various resistances and inductances may be combined to produce the required "quarter phasing" of the fluxes.

6. Explain the usual method of lagging a meter by interposing a short-circuited coil of variable resistance in the path of the flux of the voltage coil. Sketch.

7. Explain the plan of "light-load compensation" most commonly employed in adjusting watt-hour meters.

8. What three schemes are employed for "full-load compensation" in adjusting watt-hour meters? Explain in detail.

SECTION XXII CHAPTER I

TELEPHONY

TRANSMITTING AND RECEIVING APPARATUS

The character of a musical note or articulate speech is determined by three things:

First. The pitch. This is the **rate** of vibration of sound waves. It varies from as low as 60 vibrations per second in the bass voice of a man to 1,000 vibrations per second in the shrill voice of a child.

Second. The timbre. This is the **quality** of the vibration. It is determined by the number of over-tones. This is what distinguishes between the note of the piano, a flute, and a cornet. Most sounds do not consist of simple vibrations but are complex in character, consisting of a fundamental which involves the lowest rate of vibration and a number of various frequencies superimposed upon the fundamental. Depending upon the frequency and number of these overtones, it is possible to recognize different kinds of sounds.

Third. The intensity, that is, the **loudness** of the sound. This is determined by the amplitude of vibration. A note may have the same pitch, it may possess the same timbre, and yet the sound may be loud or soft.

Thus a diaphragm which is used in the telephone or in the talking machine may vibrate at a certain rate, which determines the pitch of the note, it may vibrate in its own peculiar way in certain portions of the diaphragm, which determines the timbre or quality of the note; and while vibrating at a definite rate and in a particular way, the amplitude of the vibrations to and fro may vary. This determines the intensity of the note.

The human ear is capable of detecting sound waves as low as 16 vibrations per second and as high as 40,000 vibrations per second. The human voice is capable of producing vibrations as low as 43 and as high as 3,000 vibrations per second. These fundamental facts with regard to sound should be understood in order to comprehend the principles of electric telephones.

Magneto Telephones

In 1876 Alexander Graham Bell invented and exhibited at the Centennial Exposition in Philadelphia the first practical tele-

phone In its perfected form it consists of a permanent steel laminated magnet, *M*, Fig 1161, at one end of which is a soft iron polar extension *P*, upon which is wound a coil *C*, consisting of No 36 silk insulated wire with a resistance of about 80 ohms. In front of this is mounted a soft iron diaphragm *D*, about 2½ inches in diameter, rigidly supported at its circumference The coil terminates at the binding posts *B-B* This instrument may be used either as a transmitter or as a receiver. If sound waves are projected against the diaphragm *D*, it will vibrate As it moves to and fro before the pole of the magnet, the reluctance of the air gap between the diaphragm and the pole is varied. The amount of magnetic flux which passes through the coil is thus altered. When the diaphragm springs away from the pole,

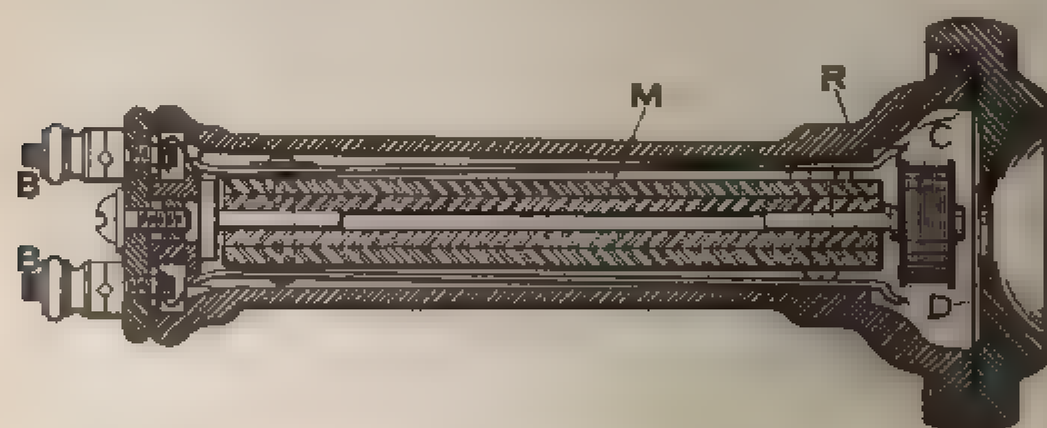


FIG. 1161.—Sectional view of single-pole permanent-magnet telephone receiver.

some of the permanent magnetic flux leaks out beneath the coil When the diaphragm moves toward the pole some of the flux finds a path of lower reluctance through the coil and through the diaphragm to its circumference on its way to the other pole This variation of flux generates an alternating e m f which is capable of producing a current in which all of the qualities involved in the pitch, the timbre and amplitude produced by the original sound waves are represented If these alternating currents, so produced, are led into another instrument, the duplicate of this one, they will flow around a similar coil *C* and alter the attraction of the permanent magnet for the diaphragm of that instrument The diaphragm is normally under tension, being drawn toward the pole. It must never touch it It is usually mounted about 1/64 of an inch away from the pole If the direction of the current due to a certain impulse

is such as to supplement the permanent magnetism, it will cause the diaphragm to be attracted a little closer. If the next impulse is in the opposite direction, it will oppose the permanent magnetism and cause the diaphragm to be released and it will spring back. The diaphragm is thus caused to pulsate in unison with the one in the transmitting instrument.

A later form of instrument is shown in Fig. 1162. This is a bipolar instrument in which the permanent magnet is curved, both poles being brought up to the diaphragm and each surrounded by a narrow coil The magnetic circuit is thus completed through the diaphragm, with the space in front of the poles as the only gap The magnetic circuit being much better,

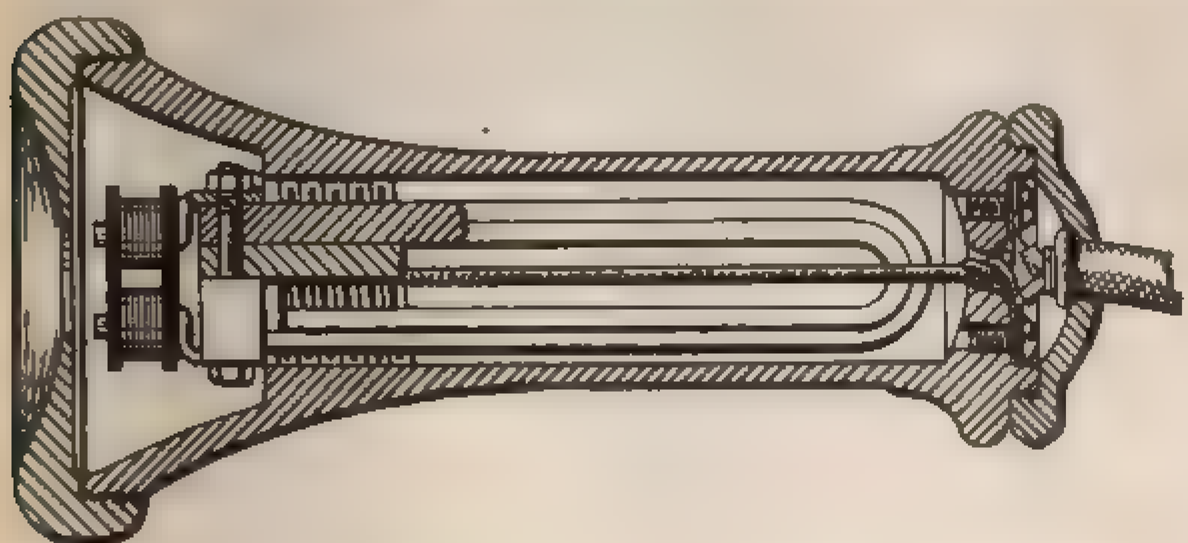


FIG. 1162. Sectional view of double-pole permanent-magnet telephone receiver.

the instrument is more powerful and the permanent magnetism more enduring.

No battery whatever is employed in this original scheme. The transmitter is virtually an alternator of the inductor type in which the sound waves due to the voice represent the power of a driving engine. It is a very inefficient device and the currents are quite feeble, hence the reproduced sound is too faint for commercial purposes.

Microphone Transmitters

After much experimenting by numerous inventors a battery transmitter was devised which superseded the magneto instrument for this purpose This type of transmitter is universally employed today It consists primarily of a loose carbon contact *C*, Fig 1163, in series with a battery, and a receiver of the

type previously described. In this case the voice is not employed to generate any current whatever, that being furnished by the battery. The diaphragm of the transmitter may be made of metal, mica, carbon, or any other thin material which will vibrate readily. If of metal, the diaphragm forms one side of the electric circuit while the carbon forms the other. The current which **normally** flows from the battery through the receiver and transmitter **is not responsible** for the actuation of the receiver diaphragm. When, however, sound waves strike the transmitter, the resistance of the carbon contact varies, due to the vibration of the diaphragm. This causes the current to rise and fall, and these variations in current cause the coil in the receiver to **vary** the attraction of the permanent magnet for the diaphragm. The transmitter is only a gate which is opened and closed more or less by the sound waves, to admit the flow of more

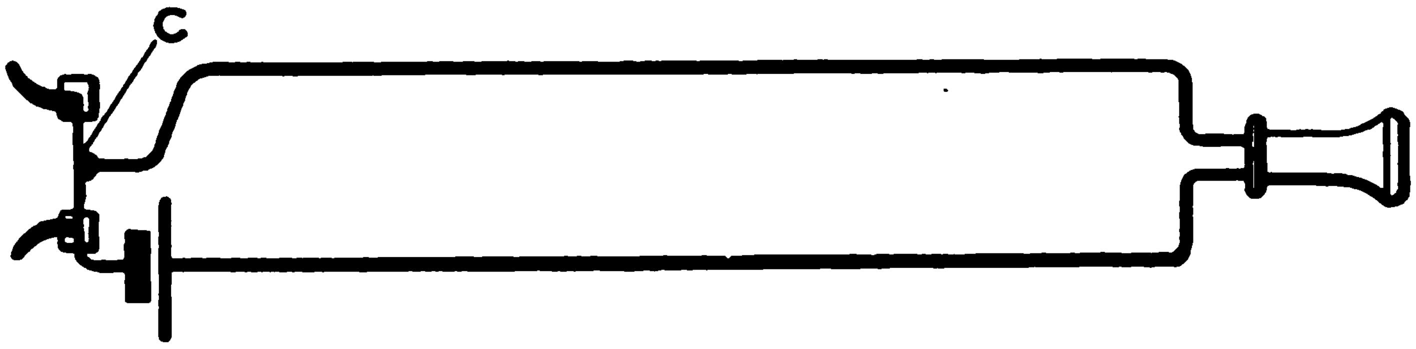


FIG. 1163.—Elementary battery telephone circuit.

or less current. It is therefore a very sensitive device. Transmitters of this sort are called microphones. This word is derived from two Greek words, "mikros," meaning little, and "phonos," meaning sound. That is, a microphone is a device which takes a little sound and magnifies it into a large sound. One of the earliest transmitters of this sort is shown in Fig. 1139. This, the Blake transmitter, consists of a diaphragm *D*, against which a platinum point, mounted on a light spring *F*, normally rests. Behind this is a hard carbon button *K* supported by another light spring *G*, *F* and *G* being connected to the terminals of the electrical circuit. An iron casting, *B*, is arranged so that the raising of the screw *J* will cause the button to be forced under greater pressure against the platinum point, increasing the tension of the contact against the diaphragm. Sound waves cause the resistance of the contact between the platinum point and the carbon to vary. The device was extremely sensitive

and could be adjusted so that it would transmit speech when the speaker was either one foot from the transmitter, by giving the spring *G* considerable tension, or it could be adjusted so that the speaker could stand 4 or 5 feet away by reducing the tension on *G*.

This transmitter was subsequently replaced by that form employing granular carbon instead of a solid carbon button. One of these is shown in Fig. 1165. Here a small box *A*, containing granular carbon, *E*, is mounted at the center of a diaphragm *D*, rigidly supported at its circumference. Insulated segments of metal are placed in the back of the box connecting

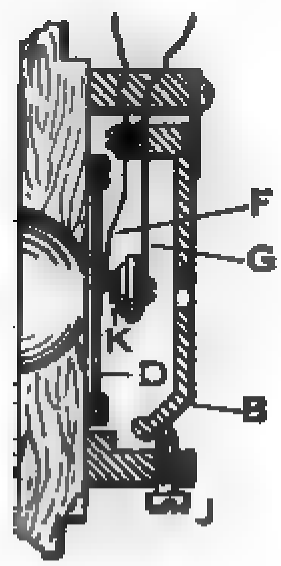


FIG. 1164. —Blake transmitter.

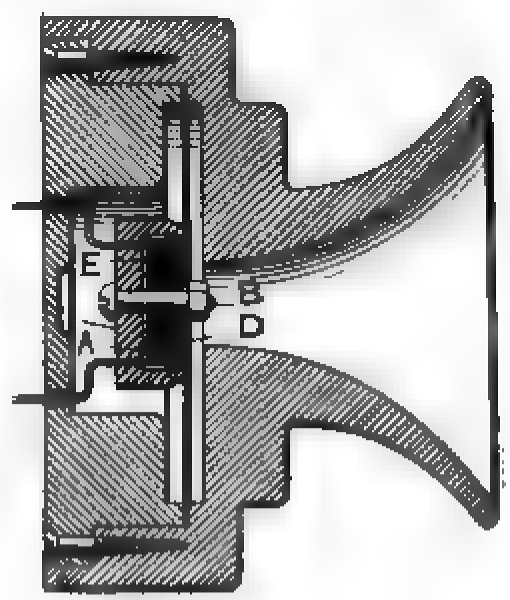


FIG. 1165.—Granular carbon transmitter.

to the electrical circuit through wires. The granular carbon forms a bridge between these terminals, and the resistance is varied by the alternate pressure of the diaphragm as it approaches to or recedes from the mouth piece.

The variation of current in a long line between the transmitter and receiver, Fig 1163, will be very small because the variation of resistance in the transmitter forms such a small per cent variation in the resistance of the entire circuit. In 1881 Edison conceived the idea of using an induction coil arranged as in Fig. 1166. He removed the transmitter from the main circuit where it produced a comparatively **small change** in the battery current and included it in a local circuit, together with the primary of an induction coil where its change in resistance

brought about a relatively **large per cent change** in the resistance of the entire local circuit. The same sound waves would now produce twenty or thirty times as much variation in current as in Fig. 1163. These pulsations were handed through inductively to the secondary of the induction coil which included the line circuit and distant receiver. This produced a magnified effect upon the receiver so that lines several hundred miles long

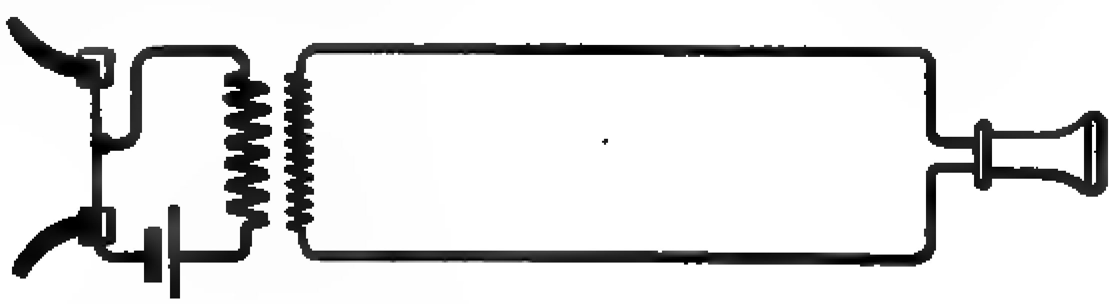


Fig. 1166.—Induction coil in simple telephone circuit.

could operate satisfactorily, whereas only short lines were practical without the induction coil. An added advantage lay in the fact that the low voltage and large current of the local circuit was transformed into a high voltage and minute current in the line circuit. This high voltage was the more readily able to overcome the resistance of the long lines and actuate still more effectively the distant receiver. Induction coils for telephone purposes of this sort have a primary resistance of about

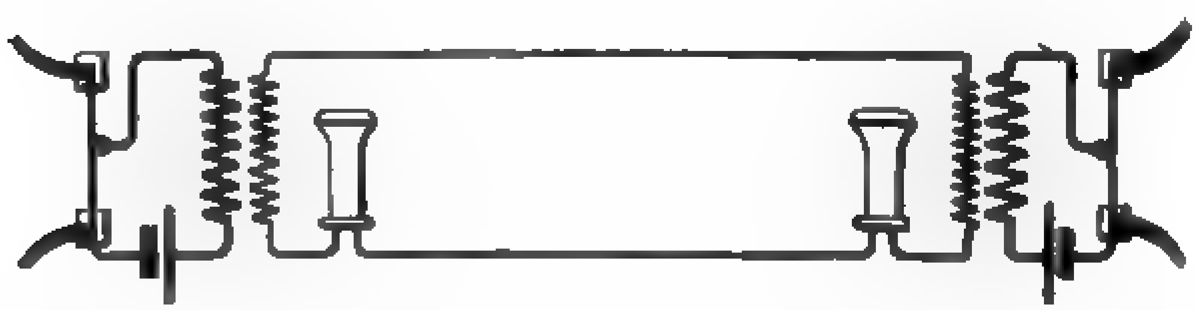


Fig. 1167.—Simple telephone circuit with local batteries, transmitters, induction coils and receivers.

$1\frac{1}{2}$ ohms of No. 22 wire and approximately 250 ohms of No. 36 wire for the secondary.

The complete talking circuits between two parties using local batteries will include the apparatus shown in Fig. 1167. The local circuit consists of batteries, transmitter, and the primary of the induction coil. The secondary circuit contains the secondaries of the two coils, the receivers, and the lines themselves.

The latter form a complete circuit, electrically insulated from the transmitters at each end, but inductively coupled thereto.

Wiring Circuits for Telephone Set

The connections for the apparatus involved in a complete telephone station for operation from a local battery is shown in

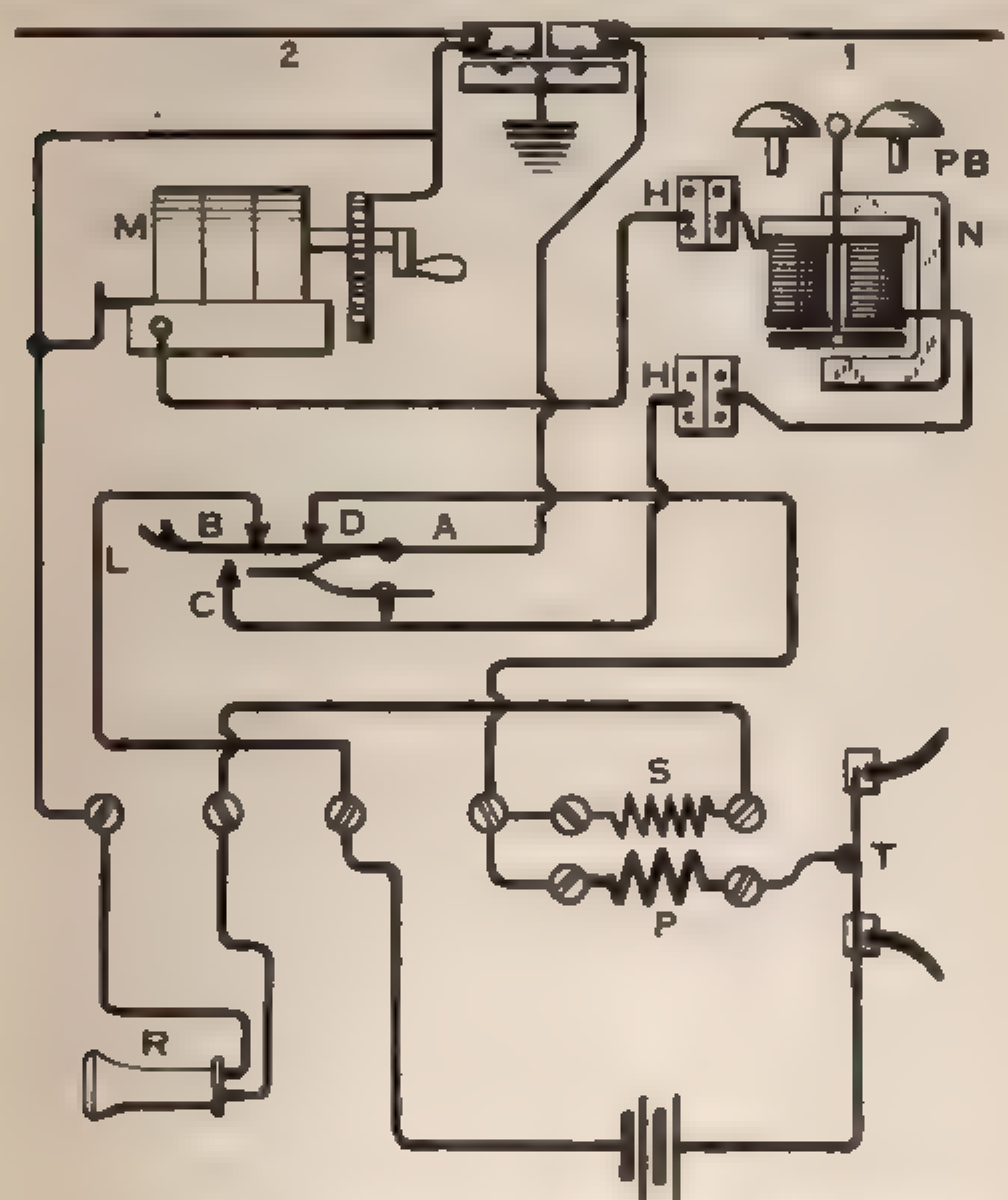


FIG. 1168. Wiring diagram for common wall-set with local battery and magneto.

Fig 1168. Early transmitters employed but a single cell of battery. Later instruments had transmitters of higher resistance so that three or four cells of wet or dry LeClanche battery are generally required.

The source of current for signaling with local energy systems consist of a magneto, *M*, which is a small permanent magnet alternator with a single coil, Siemen's H armature, rotated

through a multiplying gear by means of a handle. The signals are received by a polarized bell *P-B*. This consists of a pair of coils with soft iron cores and attached to one end of a permanent magnet *N*. At the lower extremities is pivoted a soft iron armature. The permanent magnetic flux normally passes down through both of these coils and attracts equally both poles of the armature below. When an alternating impulse is passed through the coils the permanent magnetism in one core is strengthened and in the other weakened. This causes one pole to attract the end of the armature opposite it very much more strongly than the other. This end therefore moves up, and the clapper is thrown against the bell. When the reverse alternation comes through the circuit, the magnetic flux is diverted through the other coil and that pole becomes the stronger, while the first is weakened. The other end of the armature is thus attracted and the clapper swings across to the other bell. The frequency is usually about 15 cycles per second. The bell has no make-and-break contacts; thus the magneto and bell will operate for a long time without inspection or repair.

If a call is received by the telephone it comes in over line wire 1 from a distant magneto, passes through to the point *A*, which is the pivot of an automatic hook *L*, thence if the receiver is on the hook to the lower contact *C*, thence through the hinges, *H-H*, to the door of the box on which the polarized bell is mounted and thence to the frame of the magneto and out via the line wire 2. Should it be desired to return the signal, the handle of the magneto is rotated. This instrument is normally short circuited to remove the resistance of its armature from the line. In turning the handle, however, a sliding connection is provided which automatically removes the short circuit from around the magneto and loops its armature into the line. The voltage which it generates is thus delivered through the bell coils in this instrument and the bell coils in the instrument at the other end of the line. When the receiver is removed from the hook a spring lifts it, closing the contacts *B* and *D*. The breaking of the contact *C* disconnects the polarized bells from the line. Closing the contact at *D* places the primary of the induction coil *P*, the transmitter *T*, and the battery on a closed circuit via the contact *B*. At the same time current originating in line 1 may now flow via the contact *D* and through the secondary of

the induction coil S, the receiver R, and thence to line 2. The connections thus established are the same as shown in Fig. 1167.

Series and Bridging Telephones

For working a number of telephones on party lines, two arrangements are possible. The telephones may be connected in series as in Fig. 1169, or in multiple as in Fig. 1170. When ar-

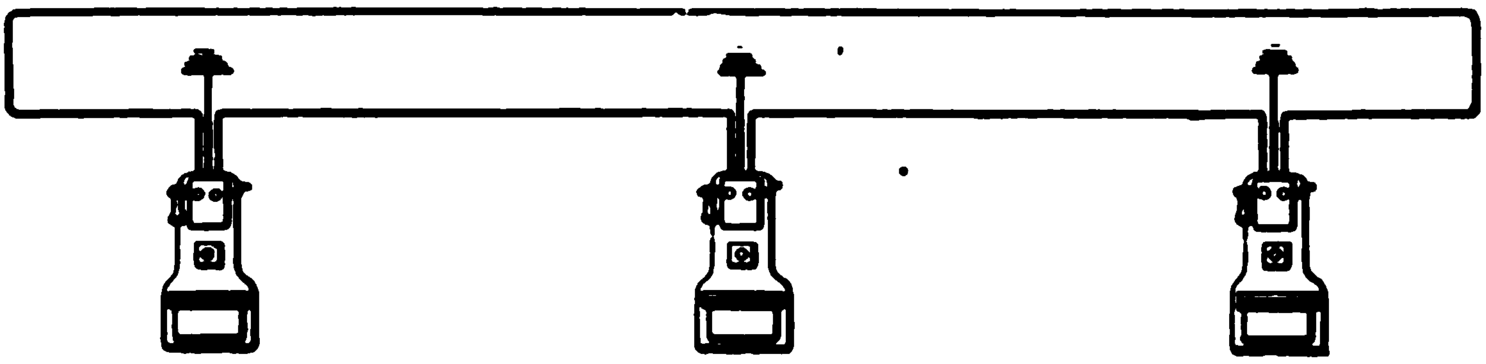


FIG. 1169.—"Series" telephone circuit.

ranged for operation in series the polarized bell magnets have a resistance of about 80 ohms and the magneto armatures a resistance of about 600 ohms. When two parties are talking on such a line all of the polarized bells that are in the circuit, with the exception of those belonging to the two instruments in use, will be encountered. While these bell coils pass without difficulty the low-frequency 15-cycle current for ringing, they offer a great impedance to the high-frequency talking currents which

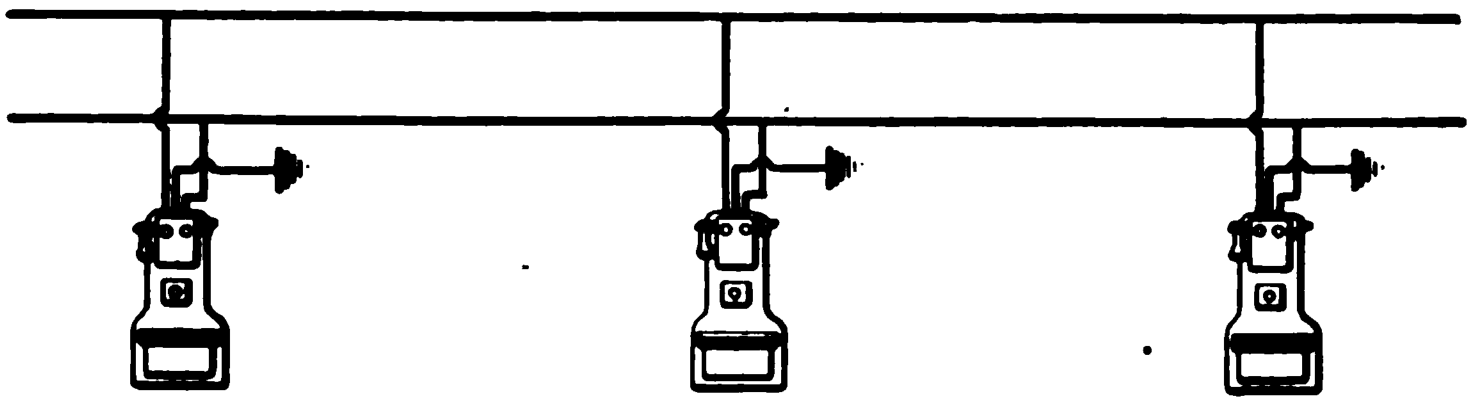


FIG. 1170.—"Bridging" telephone circuit.

are in the vicinity of 500 cycles. This impedance tends to diminish both the amplitude and the timbre of the transmitted sounds so as to render conversation difficult.

In 1890 J. J. Carty, chief engineer of the American Telephone and Telegraph Company, invented and patented the **"Bridging Telephone."** Here the polarized bell coils were wound for a resistance of 1,000 ohms, while the magneto armatures were wound for 350 ohms. The bell magnets are connected per-

manently in multiple at each instrument. When two parties are in conversation, all the other telephones have their bells connected in parallel across the lines. These bells act as shunts which will deflect some of the talking current. Their impedances, however, are so high that the actual loss is comparatively small, it being possible to work twenty to thirty phones in multiple and still obtain reasonably satisfactory results.

SECTION XXII CHAPTER I

TELEPHONY

TRANSMITTING AND RECEIVING APPARATUS

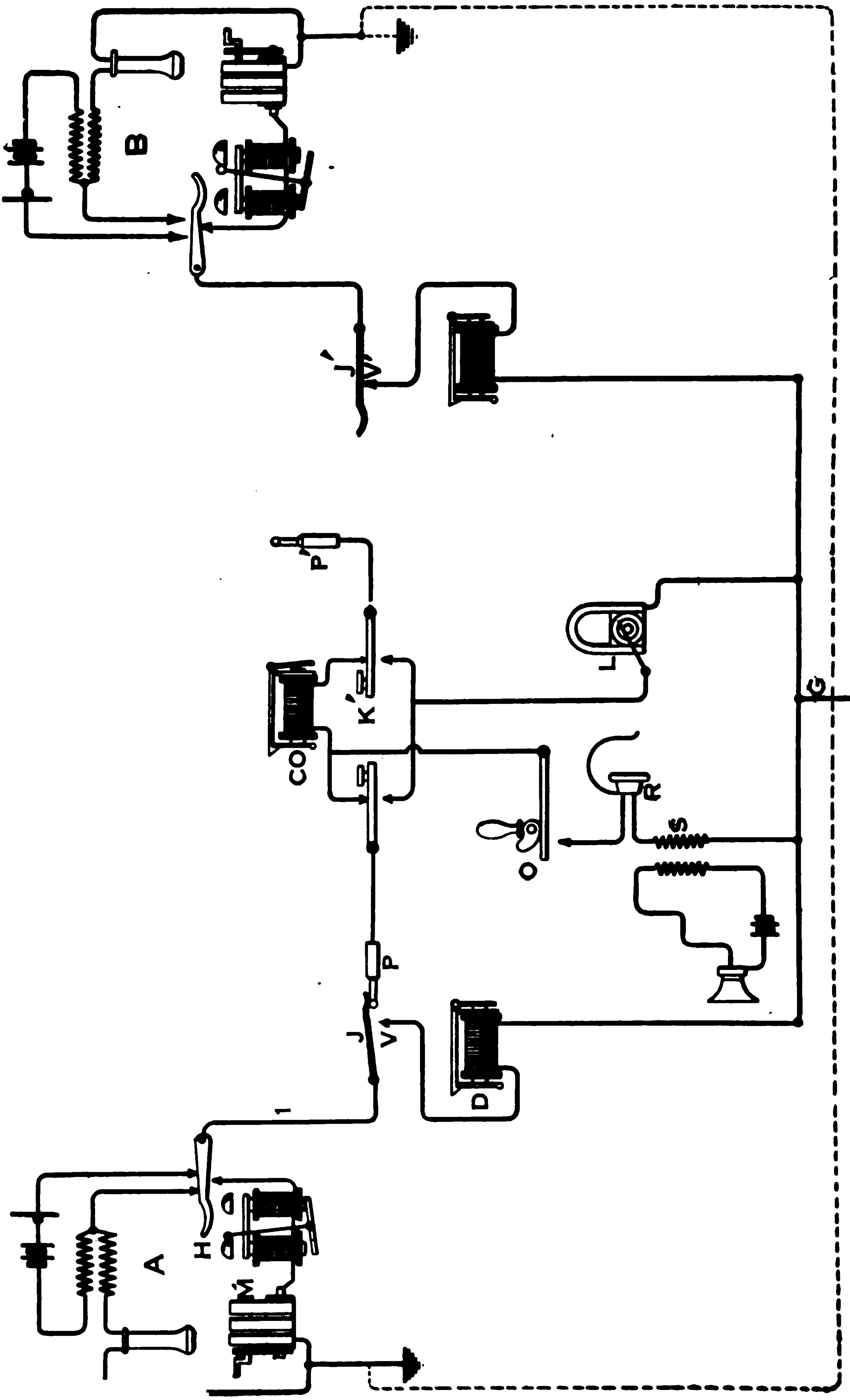
1. What is meant by the "pitch" of a note?
2. What is meant by the "timber" of a note?
3. What is meant by the "intensity" of a note?
4. Describe the construction and principle of operation of the Bell magneto telephone when used as a transmitter.
5. Explain the principle of operation of the Bell magneto telephone when used as a receiver.
6. Describe the details of construction of single-pole and double-pole receivers.
7. Explain the principle of the microphone transmitter.
8. Sketch a simple microphone circuit, and explain the action of transmitter and receiver.
9. Explain the details of the Blake transmitter. Sketch.
10. Explain the details of the granular carbon transmitter. Sketch.
11. Explain the action and advantages of the induction coil used in a simple telephone circuit. Sketch.
12. Sketch complete talking circuit between two subscribers, including transmitters, induction coils, batteries, main lines and receivers.
13. Sketch a complete circuit for a standard wall set, including local talking battery, magneto for ringing and polarized bell. Tabulate the apparatus included.
14. Sketch a line circuit, including four "series" telephones. Describe the bells and magnetos employed.
15. Sketch a circuit, including four "bridging" telephones. Describe bells and magnetos employed.

SECTION XXII CHAPTER II

TELEPHONY

TELEPHONE SWITCHBOARDS

Where a large number of telephones must be arranged for intercommunication, a central exchange for clearing the calls is required. One of the simplest arrangements of an exchange where local batteries are used at each subscriber's phone is shown in Fig. 1171. If a subscriber located at *A* wishes to obtain connection with another subscriber's line, the magneto *M* is turned, which sends a ringing current out through the lower contact of the hook *H* into line 1, thence to the central office. There the circuit passes through a line jack *J*, which normally rests on a lower contact *V*, thence down through an annunciator drop *D* or some other form of line signal and back by the ground *G* or the other wire of a metallic circuit. The alternating current energizes the drop *D*, causing it to release a shutter, thereby exposing a number corresponding to the subscriber's line. The central operator then takes a plug *P*, which is the terminal of a cord circuit, and inserts it in the jack, making contact with the upper spring and breaking from the lower, thus cutting out the annunciator drop. The operator now takes the plug *P'*, which is connected to the other end of the cord circuit, and, pressing the listening key *O*, inquires "Number, please"? This key places the operator's head receiver *R*, and the secondary of the induction coil *S*, in circuit with the subscriber's line. The primary, battery and transmitter in the central office are permanently upon a closed circuit. Upon receiving the number, the plug *P'* is inserted in the jack *J'*, which breaks the circuit through *V'* with the line signal of this party and establishes connection with the cord circuit. Upon pressing key *K'*, a current from the magneto *L* is allowed to pass out over the line to the subscriber located at *B*. When the conversation is finished one or the other is supposed to ring off. This sends a ringing current of low frequency through the lines and cord circuit, energizing the "clearing-out drop" *C-O*, which falls, notifying the operator that the cord circuit *P-P'* is no longer



—Elementary circuit between two subscribers through telephone exchange with local batteries and magnetos.

required. The plugs are then withdrawn, and the cord circuit may be used for another pair of subscribers.

In a standard switchboard there is one line signal and one line jack for each subscriber's line. There are usually about 10 cord circuits for each 100 subscribers' lines, thus permitting 20% of the subscribers to talk at once. One operator cannot serve more than about 200 subscribers, and even less than this number during a busy period of the day. Three operators may work in front of a standard switchboard in busy times and reach past one another to establish connections.

Locally Interconnected Switchboards.—When there are more than four or five hundred subscribers upon an exchange, however,

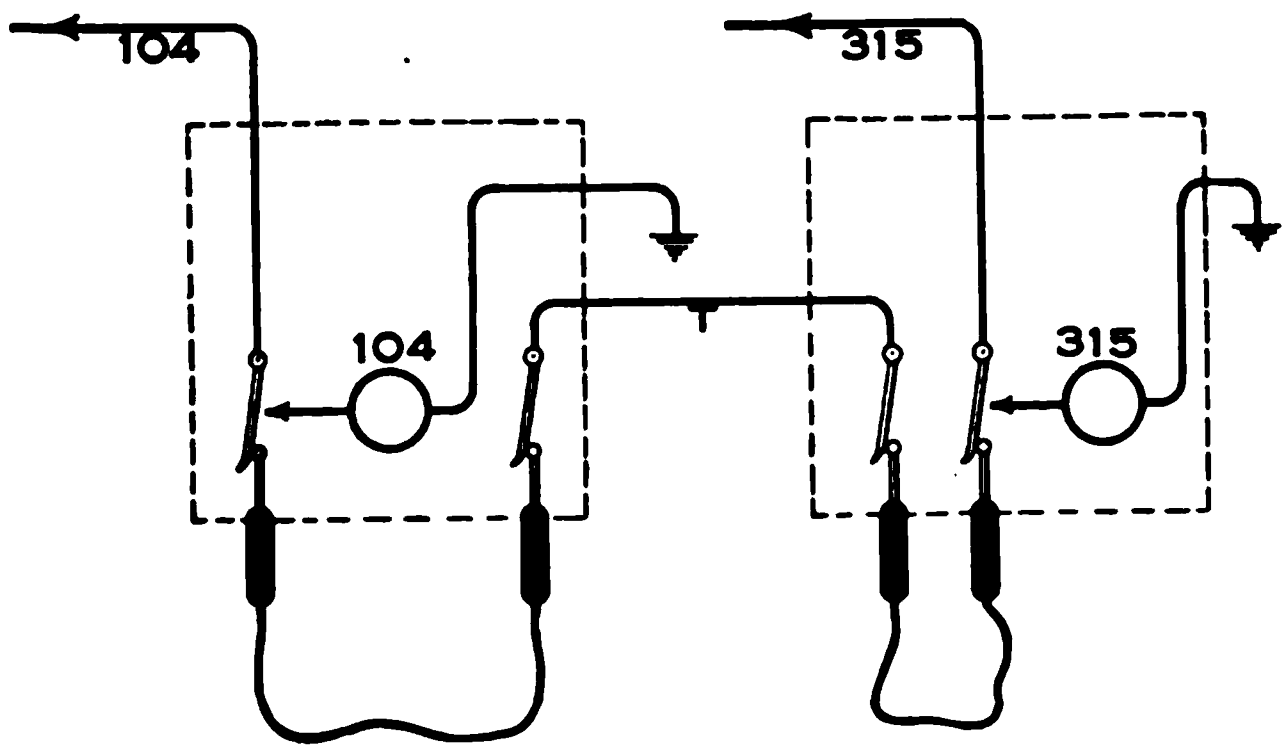


FIG. 1172.—Principle of locally interconnected switchboard.

some method of increasing the range is necessary. Two general schemes are possible. One is the locally interconnected or transfer switchboard. Here the first 200 line signals and line jacks are mounted upon one section as in Fig. 1172. The next 200 are mounted upon a second section, and so on until the entire number are cared for. Should one party in the first section call another party in that group, the same operator can establish connections through the cord circuit, but if a party—say No. 104—calls number 315, this number being connected on another section will require the operator to make connection through the cord circuit and through a transfer line T with another section of the switchboard on which this number is found. Calling the operator of section No. 2, operator number 1 will request line 315. Connection is then established by operator number two

through this transfer circuit and a cord circuit of her own. This plan requires in most instances the relaying of calls through a second operator, and the service is therefore slower than with a standard switchboard. While this plan is not often used in modern exchanges, it is frequently employed to connect different exchanges in the same city.

Multiple Switchboards.—The second arrangement is the multiple switchboard. The entire exchange of calling jacks is duplicated a number of times, as in Fig. 1173. The board is divided into sections containing from 200 to 500 line signals in each section. If the exchange has 5,000 subscribers, there will be placed above these line signals 5,000 calling jacks. In front of this section one operator may stand and reach any number of the

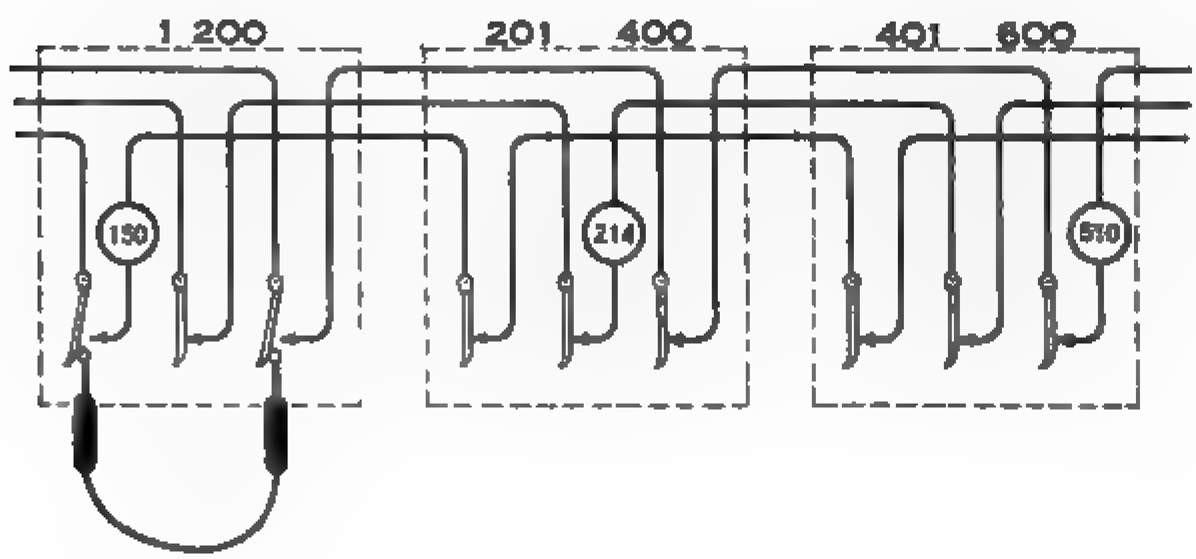


Fig. 1173.—Principle of multiple switchboard of the series type.

5,000 jacks. During a busy part of the day three operators stand in front of each section. This section is duplicated as many times as may be required, each section containing, say, 200 different line signals and 5,000 calling jacks. If there are 5,000 subscribers on the exchange and 200 line signals per operator, 25 sections will be required. On each section there will be 200 answering jacks and 5,000 calling jacks, making 5,200 per section. For the 25 sections there will be 130,000 jacks in all. Each jack has 5 or more electrical connections. From the above one may form some conception of the complications involved in a multiple switchboard installation. This plan insures very fast operation. Each operator is protected against being called save by 200 selected subscribers, but she can call any one of the 5,000 subscribers' lines and furnish connections to any of

the 200 calling lines with one operation. A busy test provides that, in case the line is already in use on some section of the board, the operator will receive a click in her receiver as she inserts the tip of the calling plug in the line jack. Special circuits are provided for this purpose.

Multiple switchboards are of two types: First, the series-multiple switchboard, in which the 25 jacks of each subscriber's line on the 25 different sections are in series. This arrangement is illustrated in Fig. 1173. The possibility of dust particles breaking the circuit in some one of the 25 electrical contacts in series makes this arrangement impractical.

The majority of multiple switchboards are of the branch terminal type. Here the 25 jacks on the 25 sections belonging to one subscriber's line are all connected in multiple instead of in series. The danger here is of short circuiting instead of open circuiting. In practice the branch terminal type has been found to be far more dependable. The continuity of the line does not depend upon the contacts in the jack.

The majority of exchanges today include multiple switchboards, the exchanges themselves being locally interconnected by means of trunk lines.

The annunciator drop which was originally used for receiving the subscriber's call was bulky and expensive. It has been entirely replaced by a small incandescent lamp occupying less than $\frac{1}{6}$ the space required for a drop and giving practically no trouble in service.

When party lines are to be operated, provision may be made for ringing any one of the parties without disturbing the other subscribers on the line. One arrangement for a four-party line is shown in Fig. 1174. Lines *L*-*L'* lead to the central exchange. Subscribers number 1, 2, 3 and 4 are shown. The bells for subscribers No. 1 and No. 2 are connected between line *L* and the ground, those for subscribers No. 3 and No. 4, between line *L'* and the ground. Selective ringing for this system is accomplished through the use of a **"biased bell"** and pulsating unidirectional currents. The usual polarized bell will ring with alternating current. If a spring is employed which holds the clapper normally against one bell, it may be made to ring or not ring with a pulsating direct current, depending upon the direction of said current. Thus, if a pulsating direct current were sent

through the coils in such a way as to cause the electro-magnets to actuate the armature in the same direction as that in which the spring was already holding the armature, this current would produce no effect upon the bell. If, on the other hand, the pulsating current were reversed in direction, one pulsation would pull the armature against the action of the spring and make it strike the other bell, and when this impulse ceased the spring would cause it to strike the other bell. Thus a pulsating current in the right direction, together with the cooperation of the spring, will make the bells ring precisely as though an alternating current were employed. If, however, a pulsating current is sent in the other direction, no effect is produced upon the bell. Now if a pulsating direct current is sent from the central office over the line L, the current will divide between the bells of subscribers No. 1 and No. 2. No. 1 is biased so that the bell will

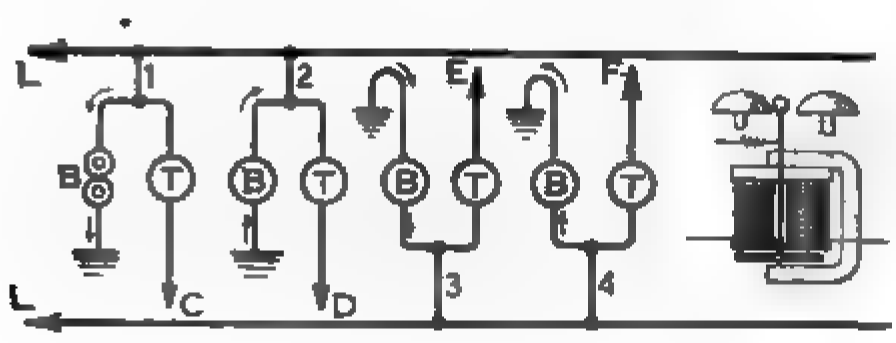


FIG. 1174.—Principle of selective ringing on four-party line.

ring, and No 2 is biased by a spring pulling the other way so that this bell will not ring Both currents return via the ground. If the operator pushes another button which sends this same pulsating current out via the ground, it will pass in the reverse way through bells No 1 and No. 2 and return through the line. This will cause bell No 2 to ring and bell No. 1 not to ring. In a similar way a pulsating current may be sent out over line L', to pass through the bells of subscribers 3 and 4 and back through the ground, while if sent from the ground through these two bells and back through the line the bell which previously did not ring would be made to ring. Thus by combinations of two circuits obtained through the two lines and ground, and pulsating currents controlled as to direction, any one of the four bells may be rung without disturbing the other three When the subscriber thus called answers, the removal of the receiver from the hook disconnects the bell circuit from the ground and places the

telephone apparatus directly across the two line wires. Thus a metallic circuit is available for talking purposes. It will be noted that there is nothing in this circuit to hinder any one listening in, the calling only being selective. In order that a subscriber on this line may reach central, the removal of the receiver from the hook closes the line circuit. This is made to actuate a relay in the central office, which in turn lights a signal lamp with a number corresponding to this line.

SECTION XXII CHAPTER II

TELEPHONY

TELEPHONE SWITCH BOARDS

1. Explain object and details of construction of a simple telephone switchboard.
2. Define a standard switchboard.
3. What limits the size of a standard switchboard?
4. Explain the principle of a "locally inter-connected" switchboard.
5. Explain the principle of a branch-terminal "multiple" switchboard.
6. Explain the principle of "biased ringing" employed on a four-party line.

TELEPHONY

CENTRAL ENERGY SYSTEMS

As the size of telephone exchanges grew the necessity for maintaining talking batteries at thousands of subscribers' stations, as well as, in some instances, magnetos for ringing the central office, involved an expense and trouble which was exorbitant, when it is considered that only about 20% of the subscribers on an exchange are ever talking at once. It will be readily appreciated, therefore, that it would be an advantage to centralize all sources of electric energy at one point. This is what is done in the **central energy** or **common battery** system. With this arrangement there is no source of either alternating or

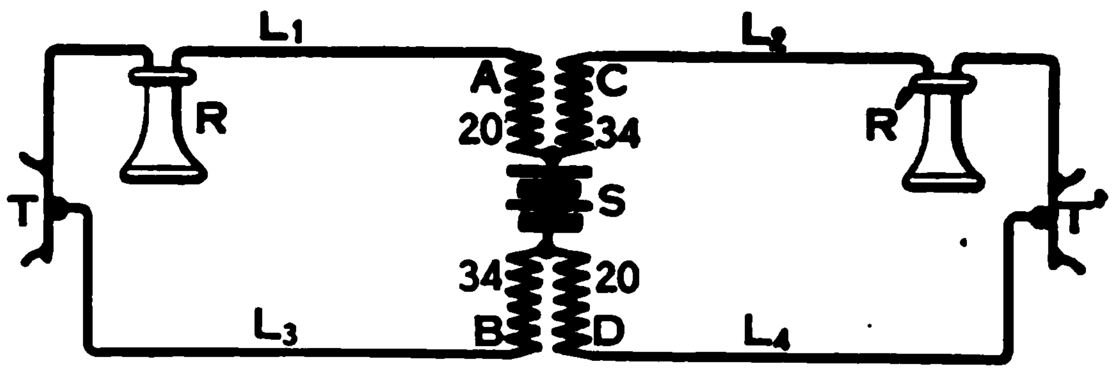


FIG. 1175.—Principle of central energy or common battery system for two telephone subscribers.

direct current at the subscriber's station. The source of power for all purposes is concentrated at the central office. The source of direct current is a storage battery of 24 volts which may be increased to 48 volts for very long lines. The source of ringing currents is a dynamotor designed to furnish about 75 volts at 15 cycles alternating or pulsating direct current for party lines. The storage battery is kept constantly charged and often a reserve battery is available in case of emergency. A simple form of central energy system is shown in the elementary diagram, Fig. 1175. Here a 24-volt storage battery *S* delivers current through a repeating coil, which divides at *A*-*C*, passing through lines *L*1 and *L*2, through the two receivers and transmitters, returning through the two sections *B*-*D* of the repeating coil, to the batteries.

These repeating coils are transformers with iron cores and a ratio of 1 to 1—that is, they have the same number of convolutions in each winding. The inside winding has a resistance of 20 ohms, and the outside winding, because of the greater length of a mean convolution, a resistance of about 34 ohms. The inside winding on one side of the battery is connected to the outside winding on the other side of the battery. Thus the total resistance of both *A* and *B* is 54 ohms, the same as the other portion *C-D*. Normally a steady direct current flows through the two telephones in multiple. Should one speak into the transmitter *T*, the current in that portion of the circuit will pulsate, due to the

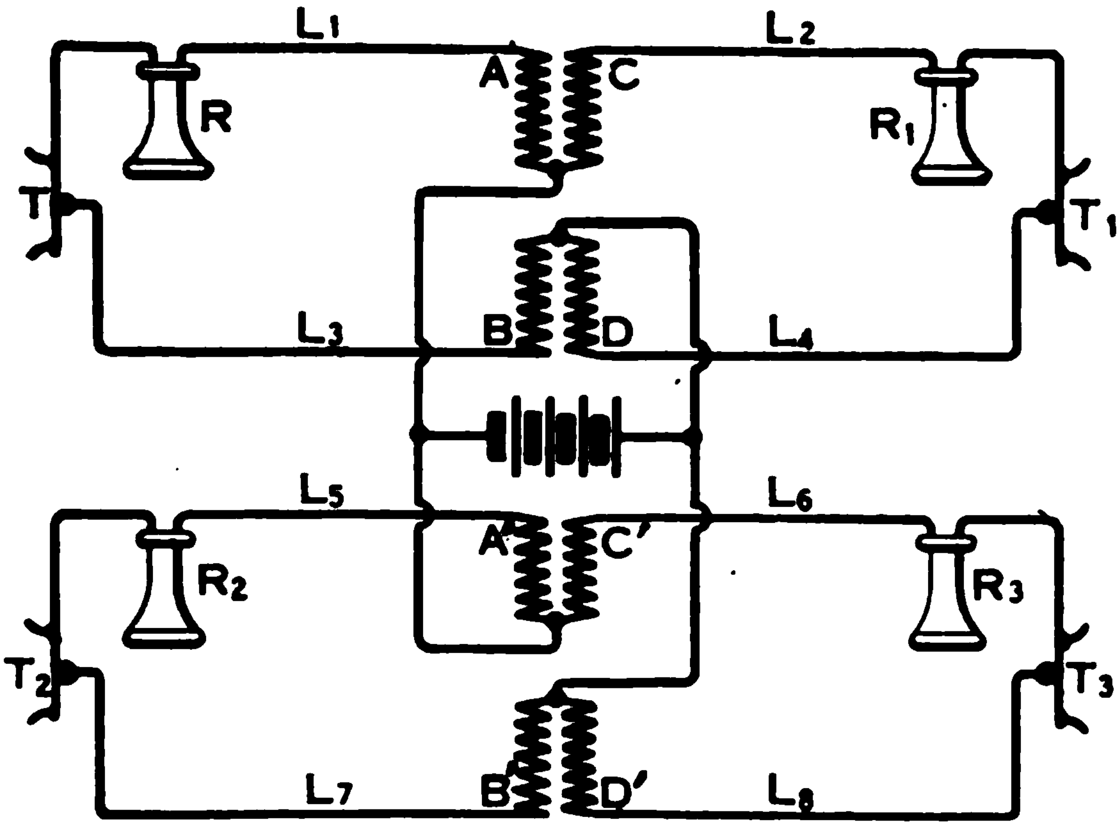


FIG. 1176.—Method of extending common battery to supply any number of subscribers' lines.

variation of the resistance. These pulsations cause the current and therefore the resulting magnetic flux to rise and fall in the windings *A-B*. This induces an alternating e.m.f. in the windings *C-D*. These alternating e.m.fs., superimposed upon a circuit already carrying a continuous direct current, cause that current to fluctuate, and as it rises and falls, the receiver *R′* is actuated.

Fig. 1176 shows how this system may be extended to operate two or more sets of telephones at the same time.

Each central exchange is provided with but one storage battery, but there is a separate repeating coil for every cord circuit and the number of cord circuits is governed by the size of the exchange. The storage battery, however, need only supply current to as many subscribers as are talking at one time.

A more detailed circuit, showing the apparatus at the subscribers' phones and the connections through the central ex-

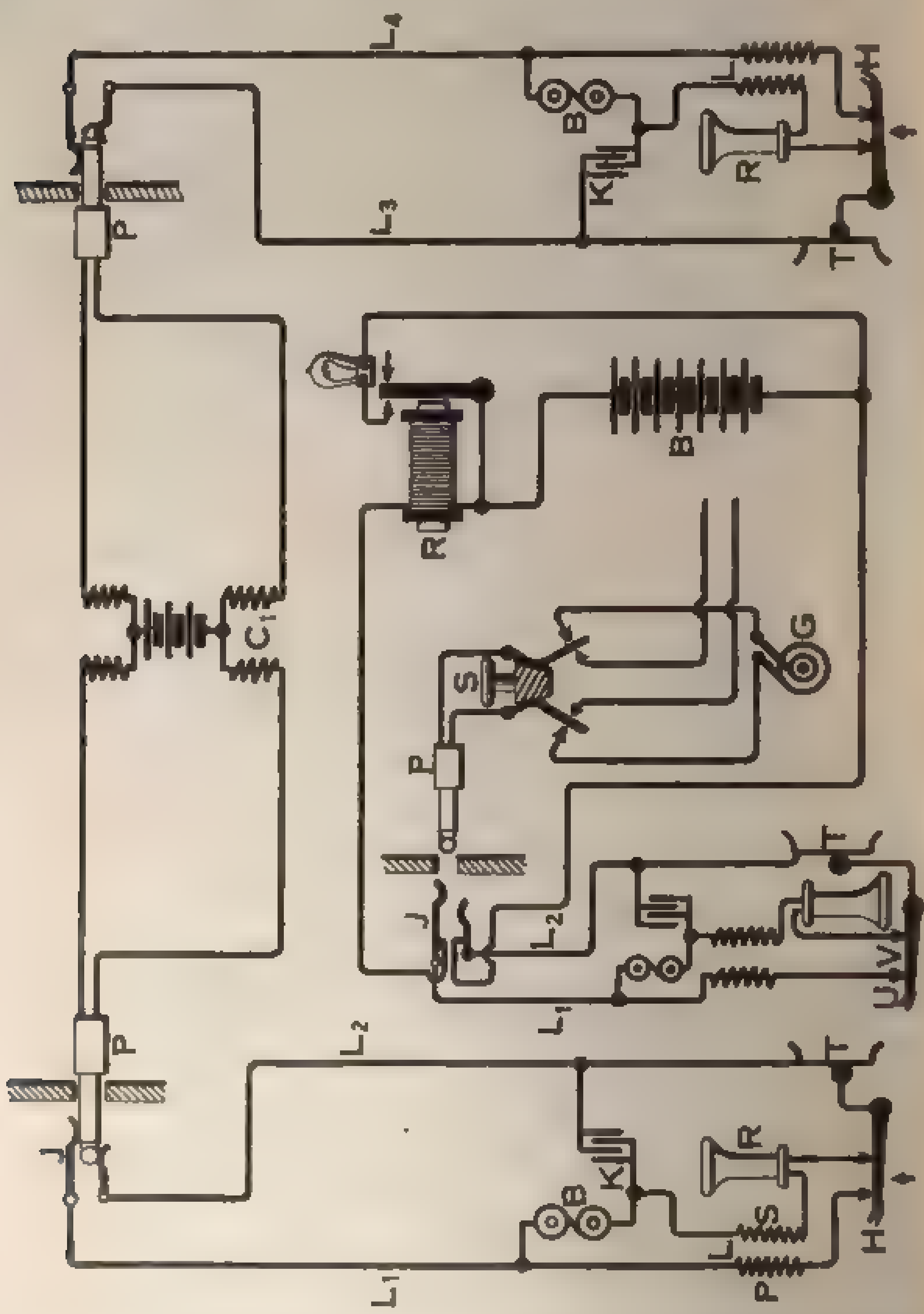


Fig. 1177.—Calling, talking and ringing circuits for central energy system.

change in the Hayes system used by The Bell Telephone Company, is shown in Fig 1177. The apparatus in each subscriber's station consists of a transmitter *T* of from 30 to 90 ohms resist-

ance, requiring a current of from 0.15 to 0.17 ampere; a receiver *R*, having a resistance of 80 ohms; a polarized bell, *B*, with a resistance of 1,000 ohms; an induction coil *L*, having a primary consisting of 2,600 turns of No. 24 wire with a resistance of 15 ohms, and a secondary *S* consisting of 1,300 turns of No. 33 wire with a resistance of 30 ohms, the secondary being wound next to the core and the primary on the outside; a condenser *K* with a capacity of 2 microfarads, and an automatic hook *H*. When the receivers are on the hook at both stations the line is open, but the condenser *K* neutralizes the self-induction of bells *B*, so that alternating current of the proper frequency will pass between lines *L*1 and *L*2 via this circuit. If the plug *P* is inserted in the jack *J*, the receiver being on the hook and the circuit open at *U-V*, when the key *S* is depressed the current from

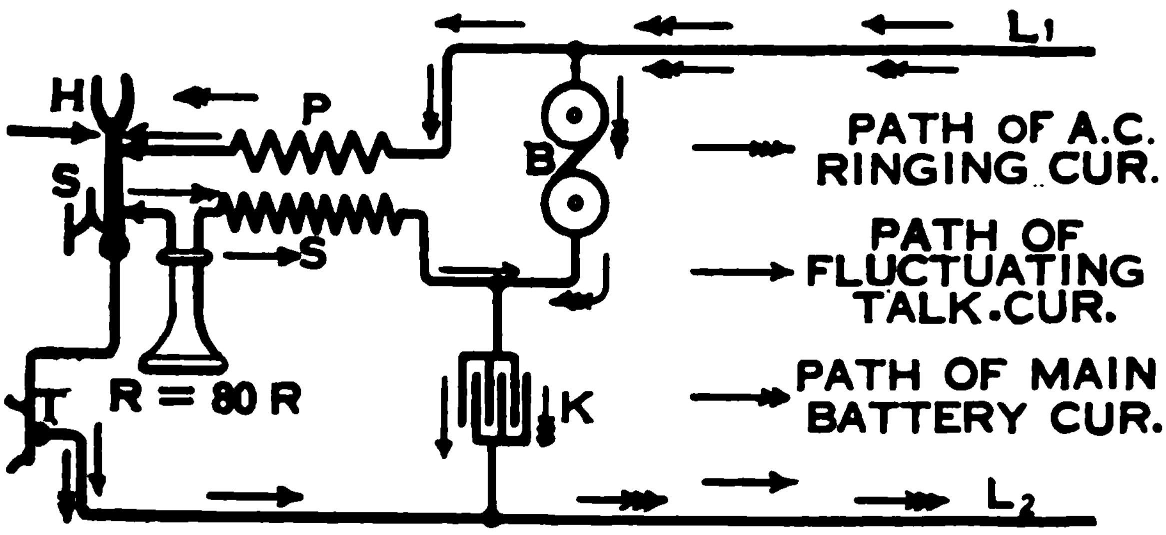


FIG. 1178.—Paths of various currents in subscriber's telephone on a central energy system.

the 15-cycle 75-volt dynamotor *G* passes through the plug and jack contacts via the line *L*1 and *L*2 and the bells will ring. In order that the subscriber may signal the exchange, the receiver is removed from the hook. The jack is normally in the position shown at *J*. The spring closing the contacts at *U-V*, current from a storage battery *B* passes through a line relay *R*, thence through the jack contact via line *L*1, contact *U* and the hook, transmitter *T*, back via line *L*2 to the negative side of the battery. The armature of the relay is attracted and connects a lamp (numbered to correspond to the subscriber's line) across the battery. There is one line relay and one line lamp for each subscriber's line entering the exchange.

The paths of the various currents flowing through the subscriber's phone may be understood from a study of Fig. 1178. The alternating ringing current entering by line *L*1 with the

receiver on the hook and the circuit open at the upper hook contacts, will pass through the bells *B* and the condenser *K* to *L2*. When the receiver is off the hook the contacts close, and continuous current from a storage battery passes over *L1*, through the primary of the induction coil *P*, thence via the transmitter *T* and back over *L2*. Variation in the resistance of the transmitter causes this current to fluctuate. The alternating e.m.fs. induced in the repeating coils now send a fluctuating current through the instrument via the following circuit: these currents come in over *L1*, but will not pass through the bells and circuit through the condenser in series, because the two-microfarad condenser develops a capacity reactance which balances the magnetic reactance of the bells, only at 15 cycles. As the talking current is in the vicinity of 500 cycles, the impedance of this circuit is prohibitive as far as the talking currents are concerned. These currents may pass, however, through the primary *P* of the induction coil and double back through the secondary *S*, and through condenser *K* to *L2*. For this circuit the capacity reactance of *K* balances the magnetic reactance of the former part of the circuit. No inductance is encountered because, to whatever extent this current passes one way through the circuit of the primary, as it doubles back through the secondary, the circuit is non-inductive, for the current flows in opposite directions in the two windings. There is, however, an inductive effect due to the excess of turns in the primary winding over the secondary. Also some of the talking currents inevitably leak through the shunt by-path from *L1* through the primary of the induction coil and via the transmitter *T* to *L2*. To whatever extent the receiver is thus deprived of talking current because of this leakage, to precisely that extent electro-magnetic induction sets in between the primary and secondary. This e.m.f. is impressed upon a local circuit consisting of the receiver *R*, the secondary of the induction coil *S*, the condenser *K*, and the transmitter *T*. The current produced in this circuit by mutual induction makes up in a large measure for the leakage of talking current around the receiver through the transmitter.

It will be observed that the induction coil is not used here for the same reason that it was used in Fig. 1167 at all, the sole object of its use here being to increase the effect of the talking current upon the receiver by that portion which is shunted around it.

SECTION XXII CHAPTER III

TELEPHONY

CENTRAL ENERGY SYSTEMS

1. Sketch a simple circuit illustrating the principle of a central energy telephone system, with two subscribers' lines. Explain principle of operation.
2. Explain the object, construction and principle of operation of the repeating coil.
3. Sketch circuits showing how two pairs of subscribers may talk without interference from a common battery.
4. When calling, how is the signal transmitted from the subscriber's phone and received by the central operator?
5. How does an operator call a subscriber?
6. Sketch the circuits and apparatus involved in a subscriber's set. Explain in detail the various circuits, and show why each particular current takes its proper path and no other.

TELEPHONY

VARIOUS TELEPHONE SYSTEMS AND CIRCUITS

The Automatic Telephone

The automatic telephone exchange is one where a mechanical device replaces the manual operator. Two general plans have been developed for this purpose. The first device was originated by Strowger, who, in 1895, brought out the first automatic telephone exchange. After ten years of experimenting the Automatic Electric Company was organized which has since established a number of exchanges, prominent among which are those in Grand Rapids, Mich.; Chicago, Ill.; and Los Angeles, Cal. The subscriber's equipment resembles the manually operated telephone. It consists of the usual transmitter, receiver, induction coil and the addition of a calling dial, a circular metal piece on the periphery of which are 10 numbered finger holes. To secure a number such as 742, the subscriber first takes the receiver off the hook, then placing his finger in the 7 hole, pulls the dial around until a stop checks it. When released, the dial returns automatically to its normal position. The subscriber is now connected to a trunk line leading to the seventh group of so-called "**connector**" switches which is designated as the 700th group. In the same manner he calls 4 and 2, in this group. He then presses a button which rings the bell of the person wanted and the connection is completed. The keyboard or internal mechanism at the exchange consists of an impulse-sending device, which, in response to the rotation of the dial, communicates to the subscriber's switch a number of impulses corresponding to the number of the hole in which the finger is placed, lifting a shaft, which occupies the central portion of the switch, up to the proper row of contacts and then brings the wiping fingers fastened thereto into connection with the proper contact on that level. The switch is about 13 inches high by 4½ inches deep and 4 inches wide. The upper half consists of two relays and three pairs of magnets. They are arranged to operate a vertical rod in obedience to the impulses sent from the subscriber's phone and bring three pairs of wiping

fingers attached thereto into connection with contact points, arranged in three semicircular banks.

Two classes of switches are employed, one known as **"selectors,"** of which there is one for every telephone connected to the exchange, the other known as **"connectors,"** of which there are ten for every 100 selectors and which are in groups, each capable of connecting 100 telephones. The function of the selector is to connect the calling telephone with the connectors in the proper group, which in turn connects with the telephone desired in that group.

A 52-volt storage battery is employed for operating the switches. The exchange has all of the refinements of a manually

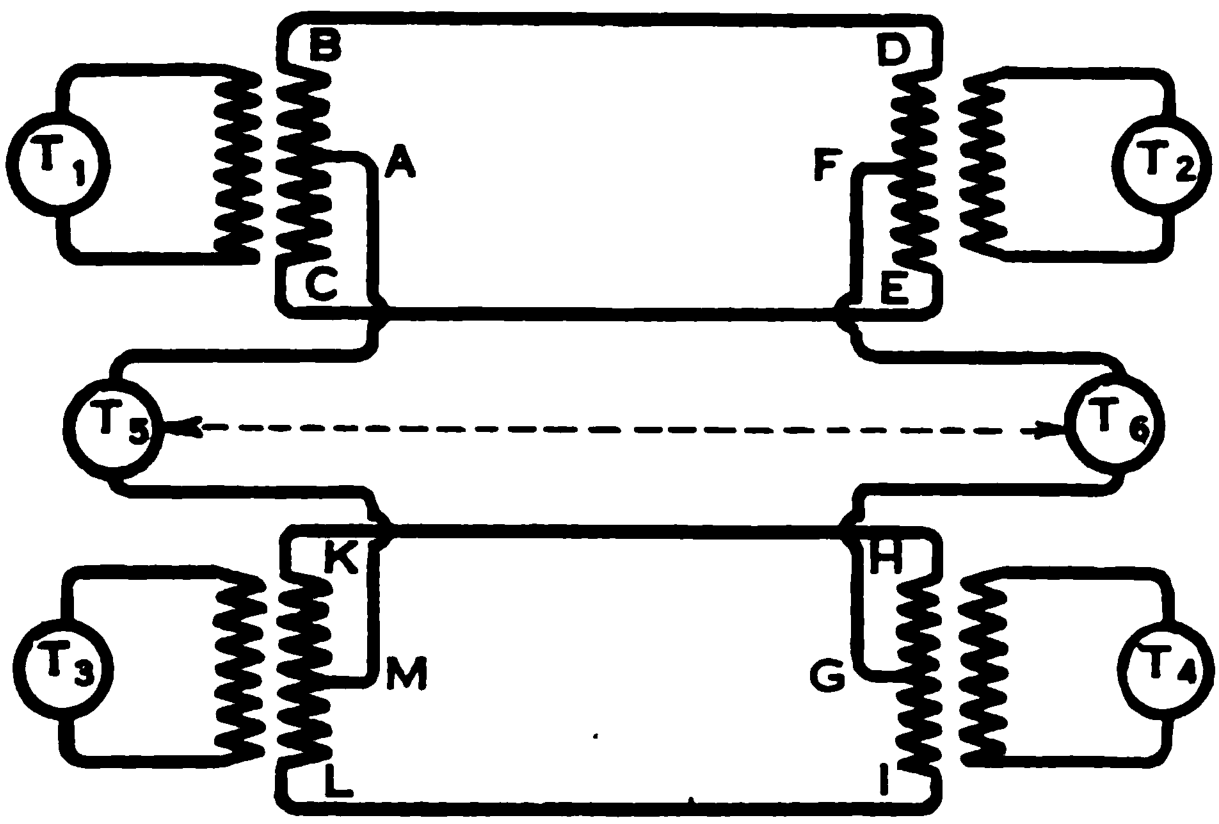


FIG. 1179.—"Phantom" line for telephone circuits.

operated exchange. The system has the advantage of requiring no operators, but one attendant being employed for supervising the switches required for every 1,000 subscribers.

The Bell Telephone Company is now installing an automatic system of their own, which is radically different from The Automatic Electric Company's system. In this automatic exchange the separate electro-magnetic switches are entirely eliminated, and constantly revolving shafts are made to engage through the medium of electro-magnetically operated clutches, a system of sliding contacts which move over the surface of a board on which are exposed the terminals of the various subscribers' lines. By means of highly refined and accurate adjustments the system

has been reduced to a practical basis and will be used in all of the large Bell exchanges of the country.

Phantom Lines

In order that toll lines may be operated at their maximum capacity a system of "**phantom**" lines has been devised which is illustrated in Fig. 1179. Here *T1* is enabled to communicate with *T2* over a metallic circuit through the repeating coils used for the purpose of insulating batteries in two cities from each other. In a similar way *T3* communicates with *T4* over another metallic circuit. Now it is entirely possible to superimpose a third conversation on these two, without interference, by connecting *T5* to the exact electrical middle point of the secondaries of the two repeating coils at one end, and *T6* to the middle of the secondaries of the repeating coils at the other end. It will be

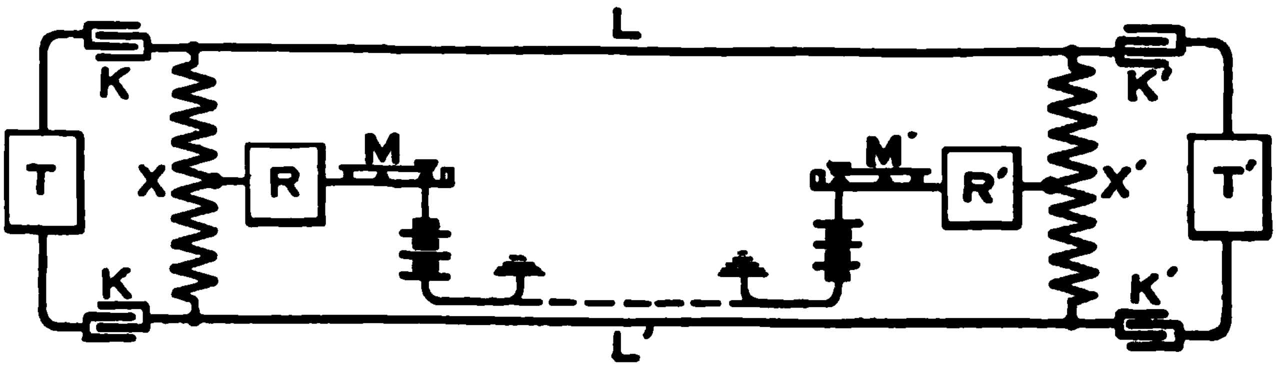


FIG. 1180.—Combined telephone and telegraph system.

observed that any talking currents entering at the point *A* will divide in opposite directions through the repeating coil to the points *B-C*, thereby producing no effect upon *T1*. Entering the repeating coil at the distant end at *D-E*, this current returns in opposite directions to the point *F*, thereby producing no effect on *T2*. Passing on through *T6* it properly actuates this instrument, then enters at the point *G* another repeating coil where it divides in proper directions to *H* and *I*, returning over the two lines of this metallic circuit to the points *K-L*, whence it leaves by the point *M* and passes to *T5*. To avoid cross talk it is necessary that the wires *A-F-G* and *M* be tapped at the exact middle points of the coils, these points being experimentally determined.

Long-distance toll lines are usually constructed of No. 12 wire. In this case the phantom lines behave as though they had the capacity of a No. 9, which is the equivalent of two No. 12 wires in multiple.

Telegraph systems may be operated over toll lines simultaneously with telephone conversations with connections shown in Fig.

1180. Here T and T' represent telephones at opposite ends of the line L-L' connected through condensers K-K and K'-K', and impedance coils X-X' at each end of the line which effectually bar the passage of any talking currents from L to L'. At the same time telegraph relays R-R' may be connected through their sending keys, and their line batteries between the ground and the middle point of the reactance coils. Such currents pass in opposite directions through the two halves of the coils to lines L and L' and therefore encounter no impedance in these coils. Thus, if current is sent from M' through R', it divides equally through the choke coil X', returns via L' and L to the coil X, entering from the two ends in opposite directions, passing to the center, whence it unites and passes through the relay R and key M to the other half of the telegraph line battery and

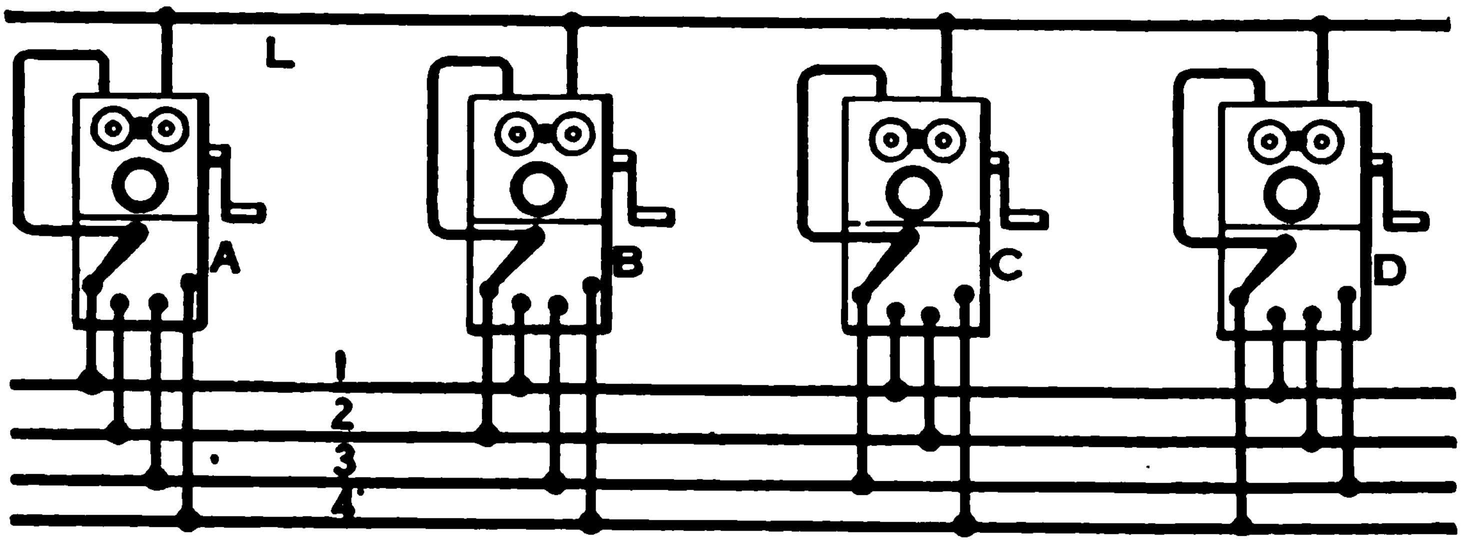


FIG. 1181.—Principle of inter-communicating telephone system.

ground. If the telegraph currents in lines L-L' are exactly equal in amount and in the same direction, they charge these lines to precisely the same potential and therefore do not affect the telephones. As the telephones are operating on a metallic circuit they do not interfere with the telegraph lines.

Intercommunicating Telephones

For intercommunication between a number of telephones it is possible to avoid the necessity for a central operator, by providing a cable containing as many wires as there are phones plus one. The connections are as shown in Fig. 1181. Here the common return L runs to all the phones. If there are four instruments, there will be four additional wires in a cable connecting to all the phones. A complete wall set with its own magneto for ringing and batteries for transmitter will be re-

quired. A switch is required on each instrument with a separate contact point for each wire in the cable. In order that any one station may call another without disturbing the other phones on the system, it is only necessary to turn the switch to the desired numbered point and ring. The circuit is completed through the wire on the cable belonging to the station called, the return being completed through the common wire *L*. Instead of the inter-communicating switch, push buttons are generally employed which lock into position when pressed and are released when the receiver is restored to the hook. By employing an additional common return wire a common ringing battery may be used with vibrating bells instead of requiring magneto and polarized bells for each station. Inter-communicating systems may be satisfactorily employed up to 15 or 20 stations. Beyond this point the number of wires in the cable and the expense make the plan undesirable.

The Brown Interior Telephone System

A simple telephone exchange employing a common ringing battery and another common talking battery for use in isolated hotels or apartment houses is illustrated in Fig. 1182. Here *C-C-C* represents the energizing coils of annunciator drops in the hotel office, while a single contact jack is shown just beneath. In each room a transmitter *T* and the primary of an induction coil are in series on the upper contact of an automatic hook, while a vibrating bell is connected through the lower contacts to a common return. The telephone receiver is on a local circuit, including the secondary of the induction coil only. The central office includes a combined ringing and listening key, *K*, in each cord circuit, with a choke coil *L*, through which the talking battery current divides. The operator's set is similar to that in the various rooms. In order to call the office, the guest removes the receiver from the hook. This permits current from the talking battery, *B*, to flow through *C-S-T* and back over the common wire, *D*. This throws the drop actuated by *C*. The central operator responds by inserting the answering plug *E* in that jack, which disconnects the drop. Tilting the key to the listening position *F*, current from the talking battery *B* passes through the choke coil, *L*, thence via the contact *A* and segment *G* of the key to *H*, thence through the transmitter and primary of the operator's set and back to the talking battery. This same current, after passing

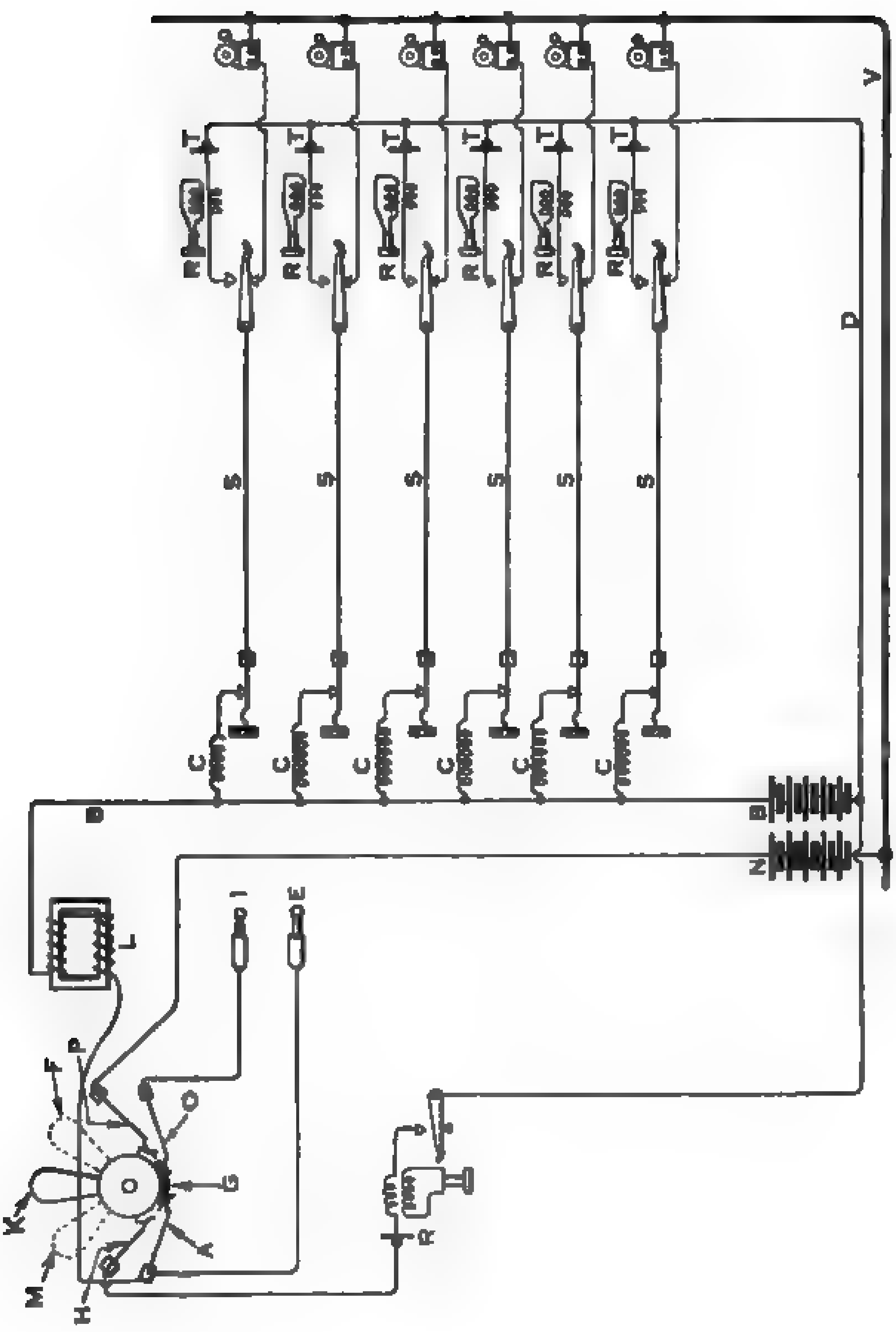


FIG. 1182.—Brown central-energy telephone system for hotels.

through *A*, divides, and goes out over the answering plug *E* and line *S* through the primary of the coil and transmitter *T* in the guest room and back over the common wire *D*. These two telephones can then communicate as in any common battery system save that the choke coil replaces the ordinary repeating coil. The choke coil is opposed to any changes of current in it. Therefore, if the resistance of either transmitter alters the current at that point, it varies the current inversely in the other transmitter, for the choke coil prevents the total current from changing.

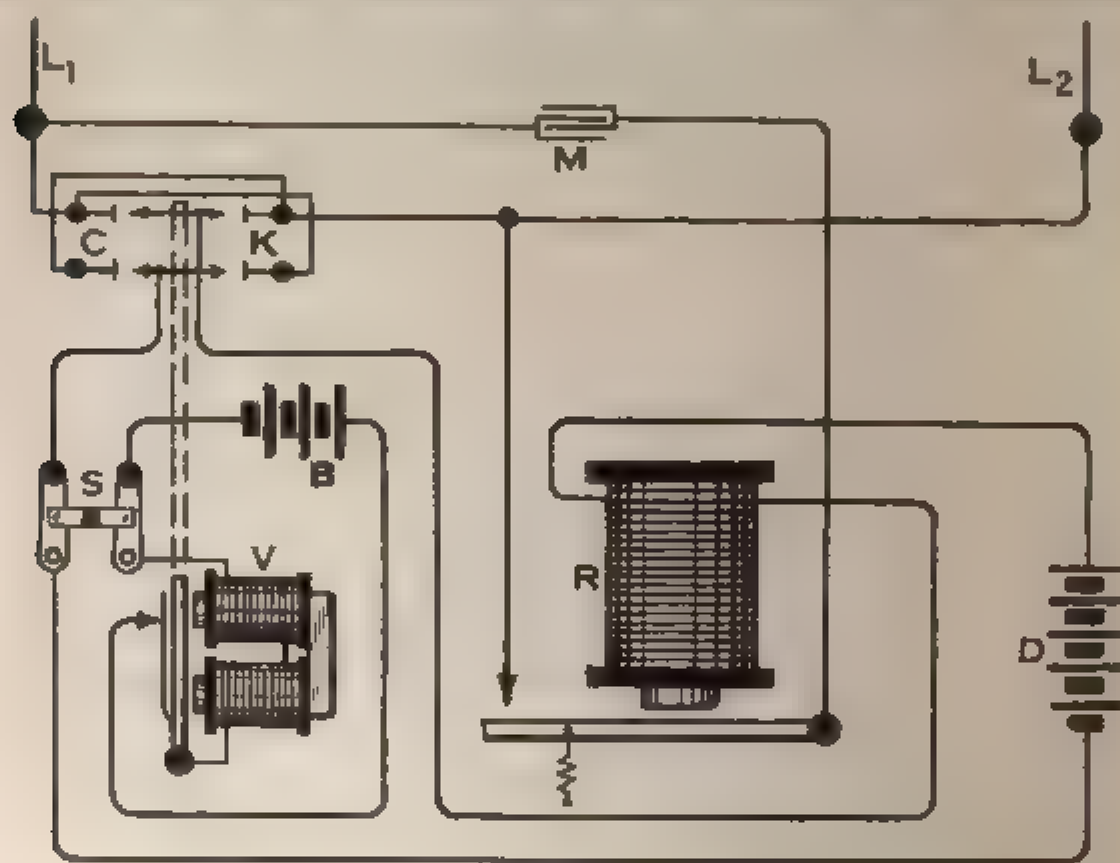


FIG. 1183.—Circuits of the "Warner" pole changer for ringing polarized bells from dry batteries.

To call another party the ringing plug *I* is inserted in another jack and the key in the cord circuit is tilted to the ringing position *M*. Current from the ringing battery *N* then passes via *P*, through the segment of the key *G* to contact *O*, thence through the jack *I* and out over another line and through the lower contact of the hook in some other room, thence through the bell and back via the wire *V* to the battery.

The Warner Pole Changer

In small exchanges it is sometimes considered unnecessary to maintain a motor-driven magneto or dynamotor, which must run all the time in order to supply ringing currents, and at the

same time the work is too laborious to require the operator to turn the handle of a magneto every time a call is desired. In such cases the **Warner pole changer** is used to advantage. This consists of a substantially constructed vibrator, *V*, Fig. 1183, operated by from one to three cells of any closed circuit battery *B*. A single cell of Edison LeLande battery will answer very well, giving continuous service for several months on one charge. The armature of this vibrator extends upward and carries four contact points, the upper two being insulated from the lower two. As the armature vibrates, these contacts are swung alternately to the right and left, closing upon *C* and *K*. Current from a primary battery *D*, usually consisting of about 50 dry cells, is led through a relay *R*, thence to the upper contact on the moving arm, and when this swings to the right, out to the A.C. terminal and thence to line *L2*, back through *L1*, and to the lower con-

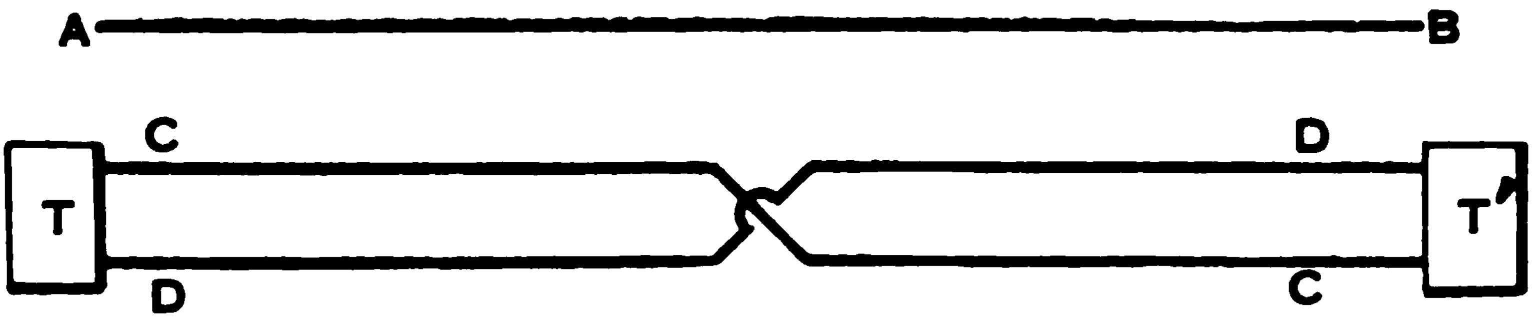


FIG. 1184.

tact *K*, whence it returns through one leg of the switch *S* to the negative side of the battery. When the vibrator swings to the left this same current is directed through the upper contact to the line *L1*, whence it returns to *L2* and finds its way back to the battery. This device rings the longest toll lines in a highly satisfactory manner. Relay *R* is employed to connect a condenser *M* across the A.C. terminals to absorb the e.m.f. of self-induction and prevent burning the contacts *C*-*K* as they open.

Line Transposition

Because of the sensitiveness of the telephone receiver to the minutest interference it is necessary that provision be made for avoiding cross talk and various inductive effects due to parallel conductors carrying alternating or pulsating currents. For this reason it is necessary to transpose the two wires of a metallic telephone line wherever they are subject to disturbances, so that both sides of the telephone circuit will be equally subjected to the

electro-magnetic interferences if the line cannot be wholly removed from the inductive influences. Fig. 1184 shows the arrangement. If a transmission line *A-B* parallels a telephone line consisting of a metallic circuit on a pole line, the wires *C-D* must be transposed throughout the distance which they parallel the disturbing wire. This should be done at frequent intervals to completely neutralize the effects. Thus if *C* and *D* are of equal length, the induced e.m.f. in one direction in *C* is counteracted by the induced e.m.f. in the same direction in *D*, and the effect upon the repeating coils at the end of the telephone line is neutralized. This is the only way in which these conditions can be successfully overcome where telephone lines are in proximity to alternating-current power circuits.

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After telephone cables have been drawn into ducts underground it is desirable to test them for leakage, grounds, crosses and continuity. These cables generally consist of a large number of pairs of small wires from 18 to 24 gauge, insulated with paraffined paper or cotton, the entire group being covered with a lead sheath to exclude moisture. To detect faults in cables, a small testing outfit consisting of 3 or 4 cells of dry battery and a galvanometer, buzzer or telephone receiver are required.

Detecting Leaks or Grounds.—To detect a leak or a ground, the cable should be opened up at both ends and the wires separated from each other so that they touch nothing else, as in Fig. 1185. One end of the testing circuit is connected to the sheath of the cable and the other end to the bared end of one of the wires.

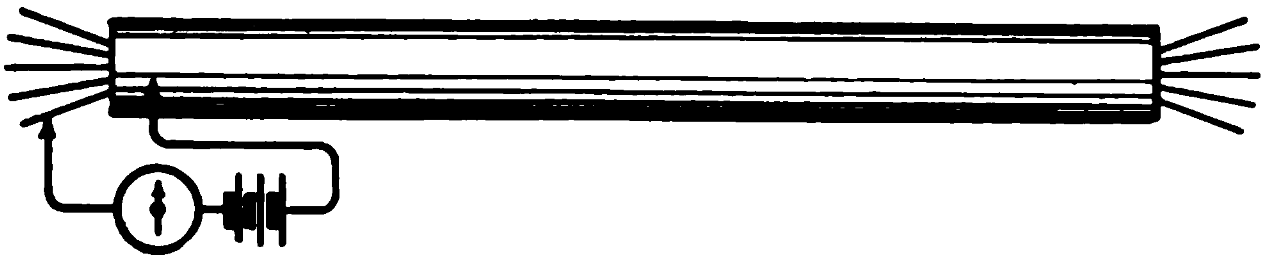

FIG. 1185.—Detecting "grounds" in cables.

If the cable is a long one, there will be a charging current flow into the cable which will give a slight deflection of the galvanometer or a click in the telephone receiver. If the connection is held closed for a moment, however, the conductor and sheath become charged and no further current will flow. Assuming, then, that the wire is insulated throughout its length, no permanent deflection or repeated click will be obtained. Each successive wire in the cable is tested in a similar manner. Should a permanent deflection or a repeated click in the receiver be obtained, a leak or ground upon that particular wire would be indicated.

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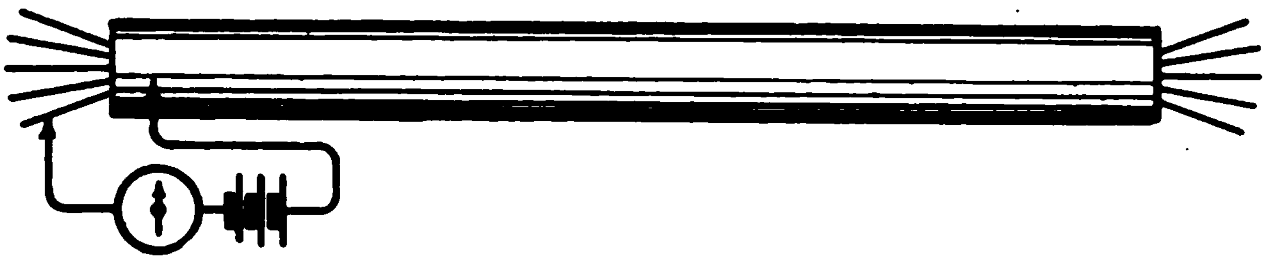

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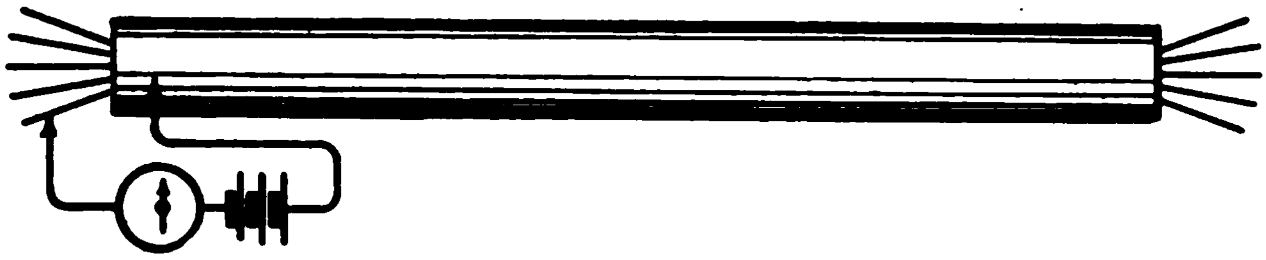

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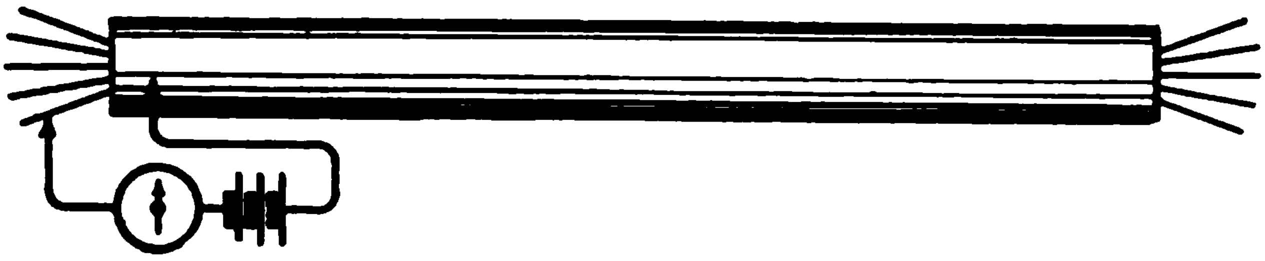

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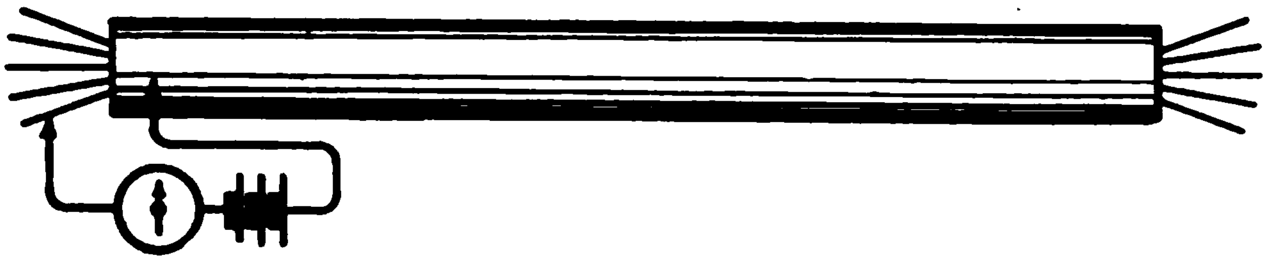

FIG. 1185.—Detecting "grounds" in cables.

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Continuity Test.—Sometimes the strain put upon the cable in drawing it into the duct breaks one or more of the conductors therein. A test must be made to determine whether or not any of the wires are broken. The connections remain the same as

above except that all of the wires at the distant end of the cable are tied together and grounded on the sheath. Under these conditions the failure to get a permanent deflection of the galvanometer or a repeated click in the telephone receiver is evidence of a broken wire.

Detecting Crosses.—To determine whether or not the insulation has been broken between any two wires in the cable so that they become crossed upon each other, the connections in Fig.

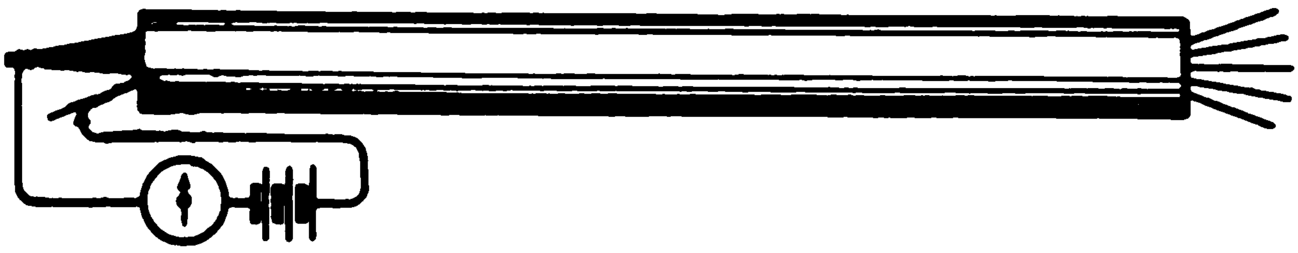

FIG. 1186.—Detecting "crosses" in cables.

1186 should be established. The wires at the distant end of the cable are separated from each other. At the testing point all the wires are bunched together and connected to one side of the testing circuit. One wire is then removed from the bunch and connected to the other side of the testing circuit. In the absence of a permanent deflection, this wire is known to be clear of a cross with any of the wires in the bunch. It is then laid aside, and another wire is removed from the bunch and connected to the opposite side of the testing circuit. Each in turn may thus be tested and its condition determined. Should a

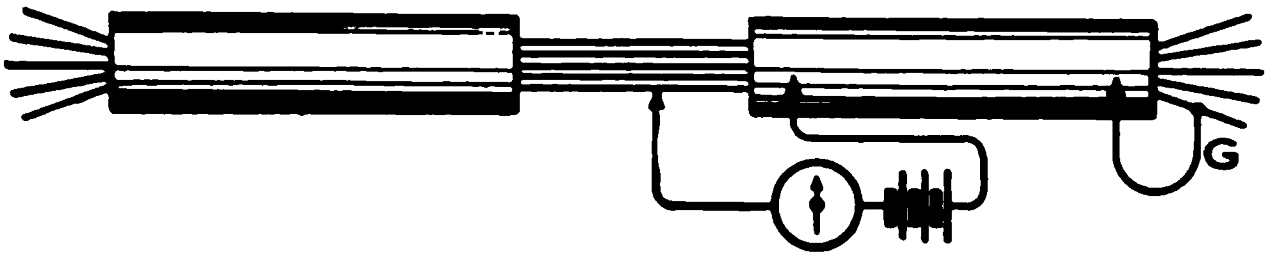

FIG. 1187.—Identifying a particular wire in a cable.

permanent deflection be obtained, that particular wire is crossed on some other wire in the bunch. This wire is now tied to one side of the testing circuit and the rest of the bunch is opened. The other end of the testing circuit is then touched upon each of the other wires successively until the one on which the first wire is crossed is indicated by a deflection.

Identifying Wires. It is sometimes desirable to identify a particular wire in a cable for use at a certain point. To do this the wire designated is grounded at the end of the cable or at

the telephone exchange, as shown at *G*, Fig. 1187. At the point where the wire is to be identified the lead sheath is removed and the wires are separated from each other, but the insulation upon each wire is not disturbed. One end of the testing circuit is grounded on the sheath. The other end terminates in a steel sewing needle. This is used to prick the insulation of each wire in turn. As only one wire in the cable is grounded permanently, a deflection will identify that particular wire.

Identifying Wires by Pairs.—It is sometimes desirable to arrange the wires in a cable at one end so that they may be numbered in pairs and subsequently identified from the other end without the necessity of going back and forth or of employing two men for the test. Cables are often constructed with red insulation upon one wire and white upon the other, these two being twisted together in pairs throughout. Such cables often

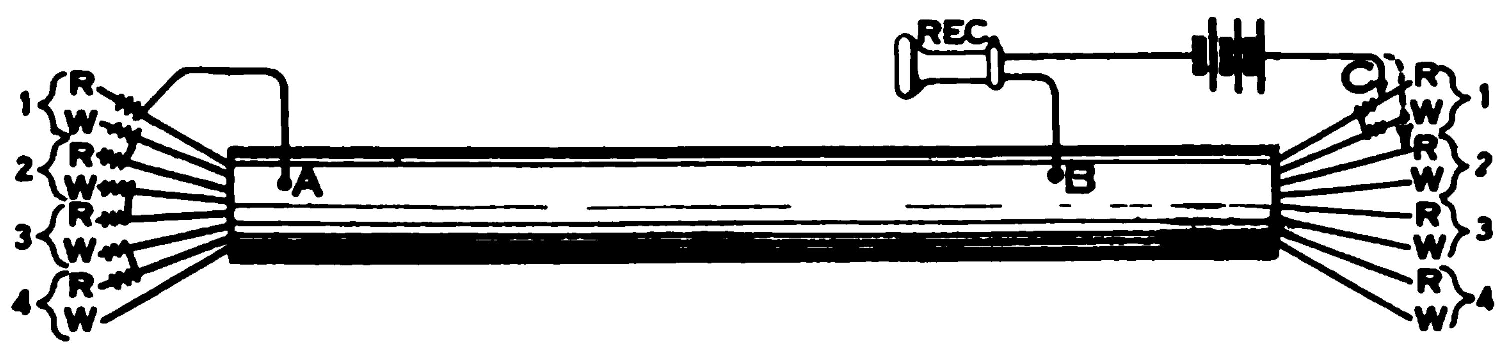

FIG. 1188.—Identifying wires by pairs in cables.

consist of a large number of pairs. The first step is to ground the red wire *R* of the first pair at the point *A*, as shown in Fig. 1188. The white wire *W* twisted with it is next electrically connected to the red wire of pair number 2, the white wire of pair number 2 to the red wire of pair number 3, and so on through the cable. These pairs are tagged as shown. Proceeding to the remote end of the cable, a testing circuit, which may consist of a telephone receiver or buzzer, and a battery, is grounded at one end *B*. The other end of the testing circuit, *C*, is now used to explore the bare ends of the wires to find a red wire which is grounded. A repeated click or buzz indicates the red wire of pair number 1. The white wire twisted with it is now electrically connected thereto. This extends the ground on the red wire from the *A* end of the cable to the *B* end, where it has just been connected to the white wire of number 1 pair. The ground is prolonged through the white wire back to the *A* end where it had previously been connected to the red wire of the pair No. 2.

The end of the testing circuit C is now advanced to find another red wire which is grounded, and there is but one in addition to the one in pair number 1. When this has been indicated it is tied together with the white wire with which it is twisted and tagged pair number 2. This is continued until all the pairs in the cable have been identified.

Measurement of Insulation Resistance

The measurement of insulation resistance of high values may be made by the **proportional deflection** method. For this purpose a standard resistance box R, Fig. 1189, a sensitive galvanometer G and shunt S, and a battery B, preferably of 100 cells, should

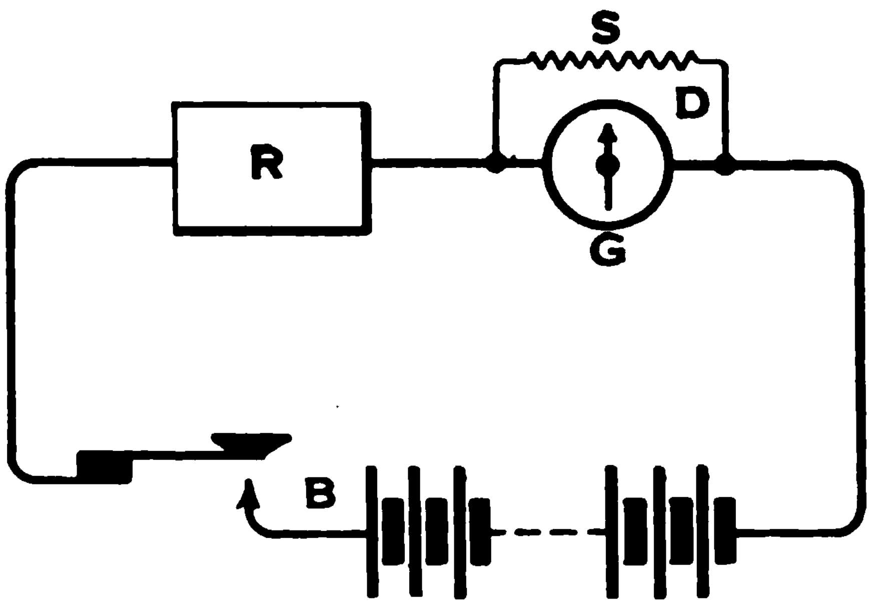

FIG. 1189.—Taking deflection on standard resistance.

be employed. The battery is first connected in series with the resistance box and galvanometer as shown. The standard box should preferably have a resistance of approximately 100,000 ohms. Let the deflection obtained on the box when the circuit is closed at the key, be called D. The same battery is next connected in series with the galvanometer and the insulation of the cable whose resistance is to be determined as in Fig. 1190. When the circuit is completed the deflection D' on the cable is obtained. It will be observed that the deflections in the two cases are **inversely proportional** to the resistances through which they are taken. This is to be expected, because the greater the resistance the less the current that will flow under a given potential and therefore the smaller will be the deflection. The voltage of the battery must be the same in the two cases. Calling the resistance of the standard box R,

and the insulation resistance of the cable IR, the proportion will be:

$$D : D' :: IR : R.$$

From which

$$\frac{D \times R}{D'} = IR.$$

It is probable that a shunt will be required to bring the deflections of the galvanometer within the range of the scale when the resistance box R is in circuit. Assuming a shunt with a multiplying power of 1,000 to be used and a deflection obtained in this case of 10 divisions, the equivalent value of the deflection would be 10 times 1,000 or 10,000. Assuming the resistance in the box to have been 100,000 and the deflection obtained without a

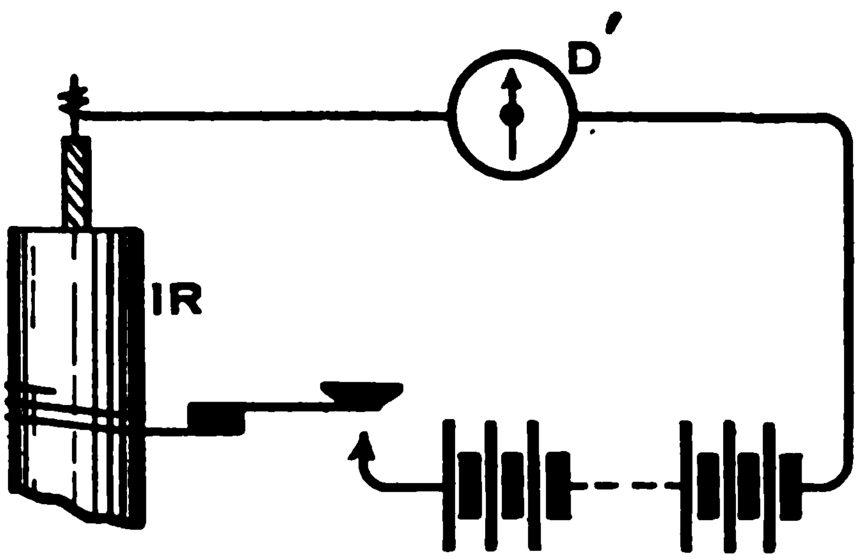

FIG. 1190.—Taking deflection on cable to ascertain insulation resistance by proportional deflection method.

shunt when the cable was inserted to be 50 divisions, the value of the insulation resistance would be:

$$10{,}000 : 50 :: IR : 100{,}000.$$

From which

$$\frac{10{,}000 \times 100{,}000}{50} = 20{,}000{,}000 \text{ ohms}.$$

Measurement of Capacity

The electro-static capacity of a cable is referred to in two ways. First, the **mutual capacity,** which is that existing between one wire and the other wire of the same pair in the cable. Second, the **total capacity,** which is the capacity between one wire and the others in the cable bunched together and grounded on the sheath. The mutual capacity is usually about two-thirds of the total capacity. To measure the capacity of a cable a balastic galva-

nometer, a standard condenser of from one to three microfarads capacity, a double contact strap key, or preferably a trigger key, and about six cells of battery are required. The connections, which include the condenser, are first arranged as in Fig. 1191.

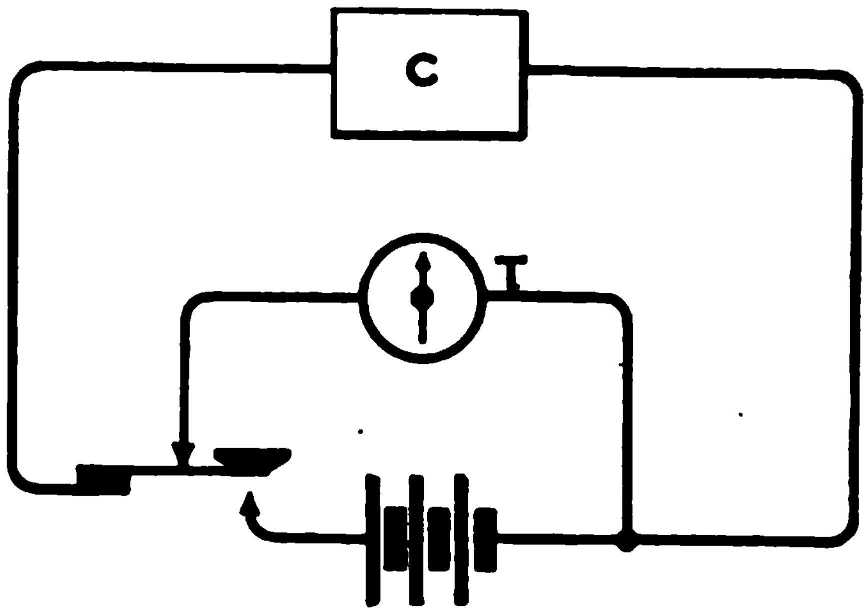

FIG. 1191.—Taking deflection on standard condenser.

The key is depressed for about 10 seconds, allowing the battery to charge the condenser *C*. The key is then released and the condenser discharges through the galvanometer. The throw in divisions is called *T*. The connections should then be changed

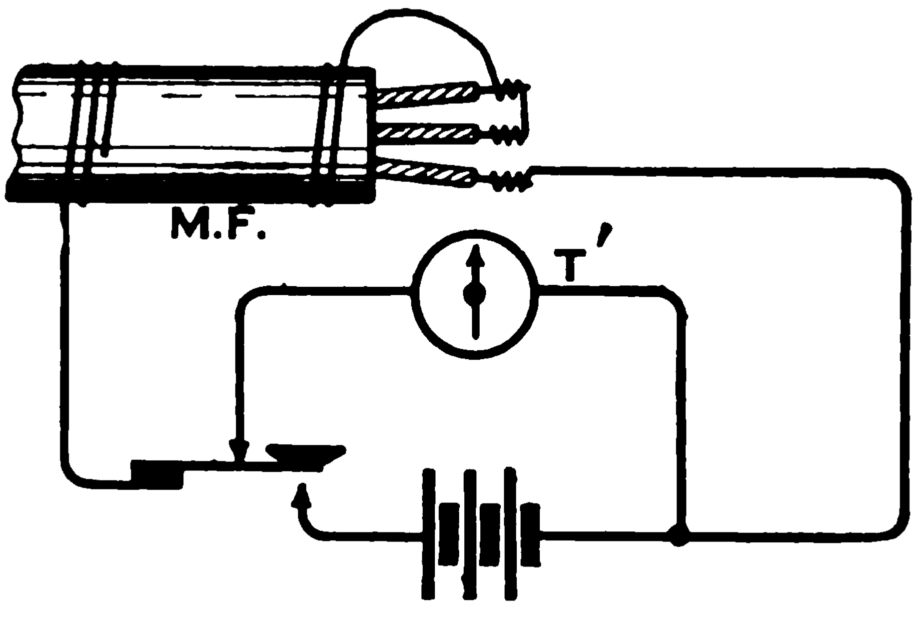

FIG. 1192.—Taking deflection on cable to ascertain its electrostatic capacity.

to include the cable whose capacity is to be measured, the circuits being as in Fig. 1192. Again the key is depressed and the battery allowed to charge the cable. After an interval of about 10 seconds the key is released and the cable discharged through the galvanometer. The deflection so obtained is called *T′*. The

capacities in the two cases are now **directly proportional** to the corresponding throws on the galvanometer. Thus:

$$T : T' :: C : M.F.$$

If the capacity of the condenser was 3 microfarads and the throw obtained thereon was 5 divisions; and if the throw obtained on the cable was 20 divisions, the expression would be:

$$5 : 20 :: 3 : M.F. = \frac{20 \times 3}{5} = 12.$$

It must be noted that in measuring the insulation resistance an **inverse proportion** is used, while in the measurement of the capacity a **direct proportion** is used. The insulation resistance measurement depends upon the **current** actually flowing through the resistance. The capacity measurement depends upon the amount of current or charge which flows into the conductor and sheath as a condenser and upon the **absence** of current flowing through the insulation. The **greater** the **resistance** involved in

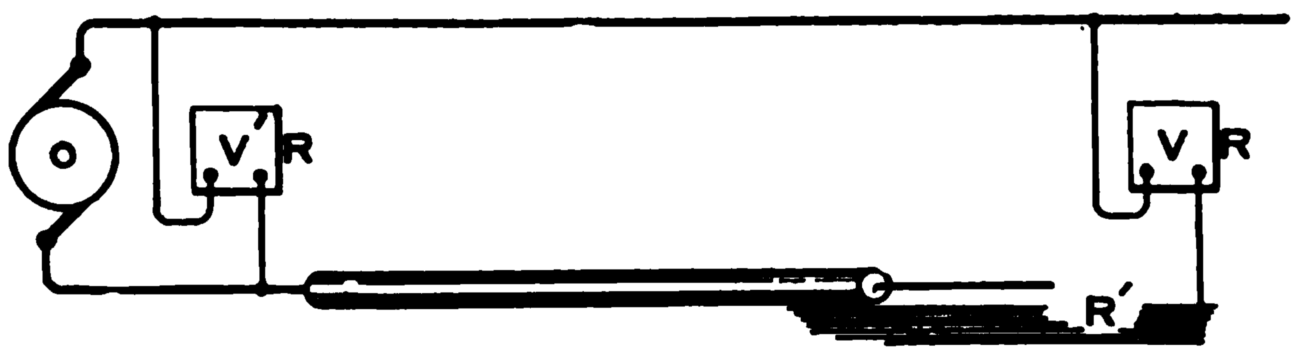

FIG. 1193.—Voltmeter method of measuring insulation resistance of one side of a wiring installation.

the insulation resistance the **less** will be the deflection. The **greater** the **capacity** involved in the capacity measurement the **greater** will be the quantity of electricity stored and the greater will be the deflection.

Resistance Measurement by Voltmeter

A simple means of measuring the resistance of the insulation of one wire of a circuit or any other resistance of limited range is illustrated in Fig. 1193. Here a voltmeter of known resistance is connected across the two wires of a generator. The deflection obtained is called V'. One side of the voltmeter is then connected to the ground and the deflection noted as the current passes from the upper wire through the voltmeter to the ground and back through the insulation to the lower wire. This de-

flection is called V. The deflection in the two cases is inversely proportional to the resistances through which they are obtained. If R is the resistance of the voltmeter and R' the insulation resistance of the lower wire, then

$$V : V' :: R : (R' + R).$$

From which

$$R' = \left(\frac{V' \times R}{V}\right) - R.$$

In a certain case a deflection of 112 volts was obtained between the two wires with a voltmeter having a resistance of 20,000 ohms. Between the upper wire and the ground the voltmeter read 3 volts. Applying these figures in the above equation:

$$\left(\frac{112 \times 20{,}000}{3}\right) - 20{,}000 = 726{,}666 \text{ ohms}.$$

With direct-current circuits and voltmeters having a range of 300 volts, insulation resistances under one million ohms can very readily be ascertained.

SECTION XXII CHAPTER V

TELEPHONY

CABLE TESTING

1. Explain how a leak or ground may be detected in a cable.
2. Explain how each wire in a cable may be tested to determine whether or not it is broken.
3. Explain how a cross may be detected between two wires in a cable.
4. How may a certain wire be identified at a particular point in a cable without removing the insulation?
5. How may wires in a cable be tagged and arranged in pairs so that a tester at the remote end may identify the pairs without going back and forth?
6. Explain a method of measuring the insulation resistance of a cable by comparison with a standard resistance, employing a battery and galvanometer. State proportion.
7. In a test for the insulation resistance of a cable by the preceding method, the deflection of a galvanometer obtained with a standard resistance of 200,000 ohms in circuit was 62 divisions, when the galvanometer was shunted with 1/99 of its own resistance. The deflection on the cable when the galvanometer shunt was removed was 124 divisions. What is the resistance of the cable?
8. Explain the method of measuring the capacity of a cable by comparison with a standard condenser employing a battery and galvanometer. State proportion.

9. If the capacity of a standard condenser employed in the above test was 2 microfarads, and the throw obtained on the galvanometer therefrom was 20 divisions, and the throw obtained on the galvanometer from the cable was 32 divisions, what is the capacity of the cable?

10. Distinguish between the "mutual" capacity and the "total" capacity of a cable.

11. Explain the "voltmeter" method of measuring the insulation resistance of a live wire. Give formula.

12. Let the resistance of a voltmeter used in the above test be 16,340 ohms. Let the voltage across the generator be 110 volts, and the e.m.f. between the negative wire and the ground be 6 volts. What is the insulation resistance of the positive wire.

13. How may this method be adapted for rapidly measuring in quick succession a large number of resistances?

14. The e.m.f. between the terminals of a generator measures 108 volts, on a voltmeter having a resistance of 18,250 ohms. When a man grasping a pair of pliers in each hand is looped in series with the voltmeter the instrument reads 68 volts. What is the resistance of the man's body?

TELEPHONY

CABLE TESTING

Where one wire is broken in a cable consisting of a number of wires of the same size, the broken point can be located by a "capacity" measurement.

Locating a Break in a Cable

In Fig. 1194 the length of the section to the break C bears the same relation to the length of the complete wire C', as do their respective capacities. To compare their capacities a good pair C'-D is connected in one arm of a Wheatstone Bridge and the pair containing the broken wire C-E is connected in a

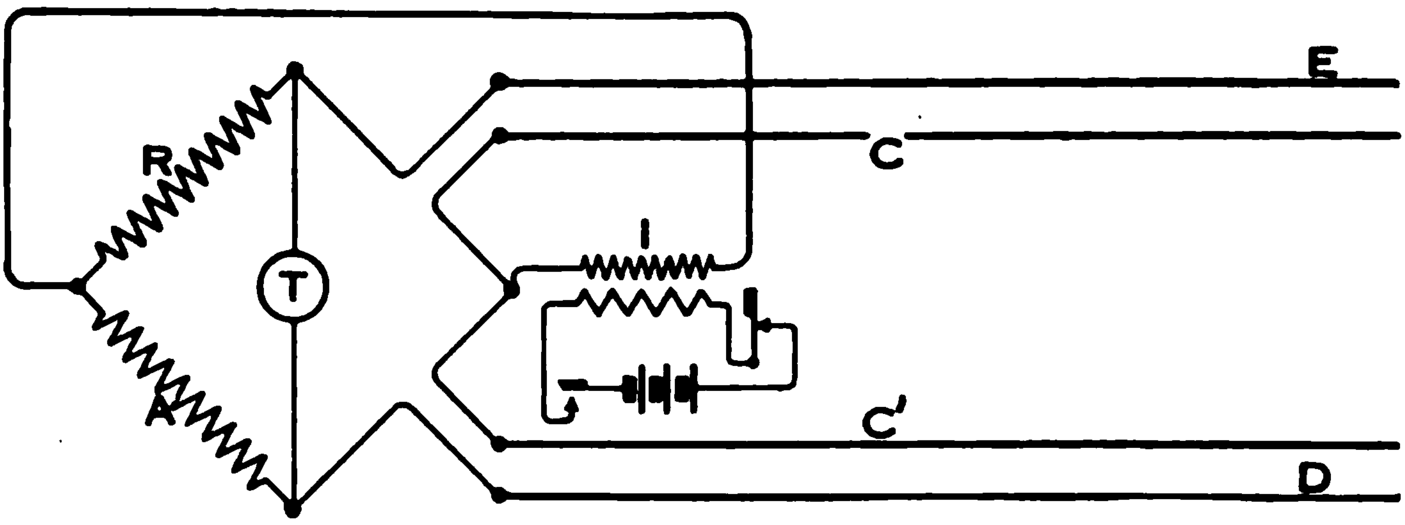

FIG. 1194.—"Capacity test" to locate break in one wire of cable when a good duplicate pair is available for comparison.

second arm of the bridge. A small induction coil I, with a vibrator, energized by a few cells of battery, should be employed to furnish alternating current to the bridge instead of direct current, and a telephone receiver T should be employed to replace the galvanometer usually found on the bridge. This will insure an audible indication of the point of balance instead of a visible one. The capacity of the broken wire and its mate is now balanced against the capacity of a perfect pair by manipulation of the resistance box R. When a balance is obtained there will be no sound in the telephone receiver. Under these conditions $A : R :: C : C'$. From which:

$$\frac{A \times C'}{R} = C.$$

It will be observed that while a direct proportion is used on a Wheatstone Bridge when all four arms consist of resistance, when two of the arms consist of capacity, balanced against resistance, the proportion becomes an inverse one.

To find the distance to the broken point,

$$\frac{A}{R} \times L = \text{feet to the break.}$$

Where L = total length of the cable one way.

In a certain case A was 100 ohms and R was 200 ohms, the length of the cable being 10,000 feet. Applying the formula,

$$\frac{100}{200} \times 10{,}000 = 5{,}000 \text{ feet to the break.}$$

To locate a break in a cable when it is the only wire in the cable and no other wire is available for comparison, it is neces-

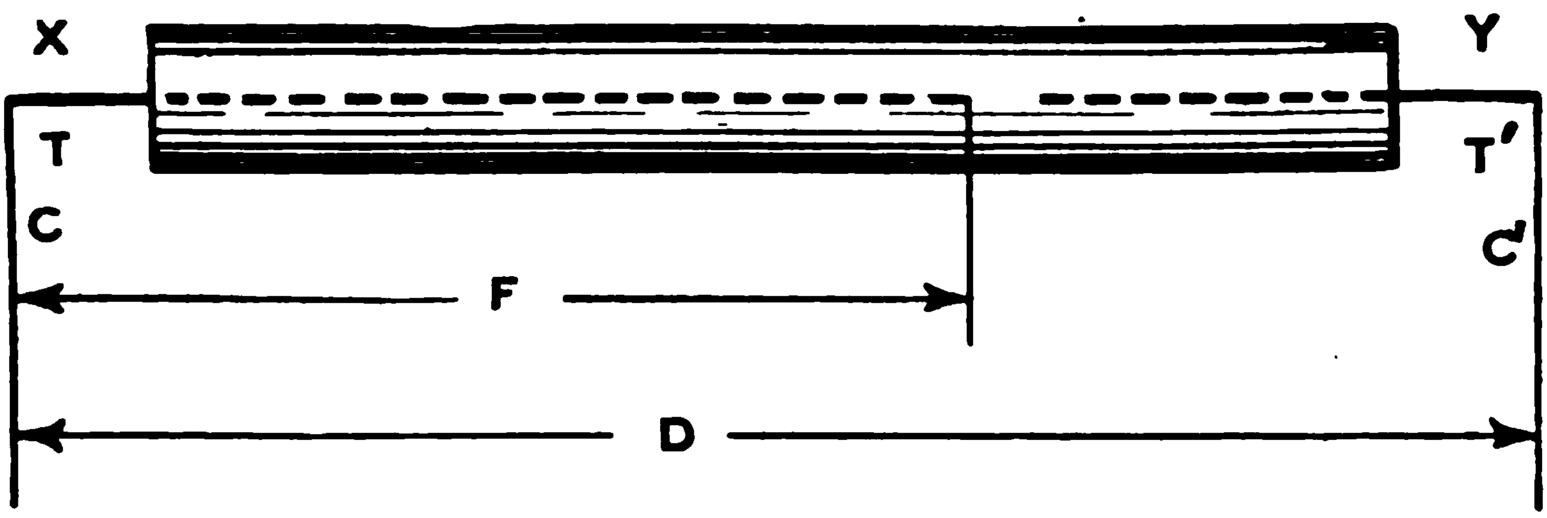

FIG. 1195.—"Capacity test" to locate break in cable when no other wire is available for comparison.

sary to measure the electro-static capacity of the two broken sections, each from its own end. It is impossible to locate such a break if the conductor is **broken and grounded.** If it is **broken only** or **grounded only** the fault can be located.

To locate a break under the conditions just set forth the apparatus employed in measuring electro-static capacity should be used and the connections shown in Figs. 1191 and 1192 employed. The letters used in Fig. 1195 have the following values:

D = total length of the cable in feet.
F = distance to break from the X end.
T = throw on the cable at X end.
T' = throw on the cable at the Y end.
C = throw on the condenser at X end.
C' = throw on the condenser at Y end.

The equation for determining the distance to the break from the X end will then be:

$$F = \frac{T \times D}{\left(\frac{C}{C'} \times T'\right) + T}.$$

If the throws obtained on the condenser at the two ends are the same, the ratio of $\frac{C}{C'}$ disappears and the equation becomes:

$$F = \frac{T \times D}{T' + T}.$$

From this it is evident that the formula is derived from a simple direct proportion in which:

$$T : (T' + T) :: F : D.$$

From which

$$\frac{T \times D}{(T' + T)} = F.$$

In a certain case $T = 20$; $T' = 10$; $C = 60$; $C' = 60$; $D =$ 30,000 feet.

Applying the formula:

$$\frac{20 \times 30{,}000}{\left(\frac{\cancel{60}}{\cancel{60}} \times 10\right) + 20} = 20{,}000 \text{ feet to break.}$$

Location of Grounds

It is not sufficient to be able to **detect** a ground in a cable, but it is necessary also to **locate** the ground. This is most satisfactorily done by means of the **loop tests.** Among the various schemes that have been developed, two will be considered: The "Varley" loop and the "Murray" loop tests.

The Varley Loop Test.—It rarely happens that any ground is of zero resistance. Furthermore, the resistance is often variable in character. If this variable resistance is included in one of the arms of a Wheatstone Bridge it will be impossible to secure a balance. If, however, it could be included in the battery circuit a balance could be readily obtained because the variation of current in this circuit does not interfere with the arms of

fixed resistance. Where a spare good wire is available for testing the circuit is arranged as in Fig. 1196, which shows the good wire and below it the bad wire, grounded at some unknown point, and through an unknown and possibly variable resistance. In the Varley loop test the good wire and the bad wire are connected together in the form of a loop at the distant end of the cable. The terminals at the testing end are connected to the X

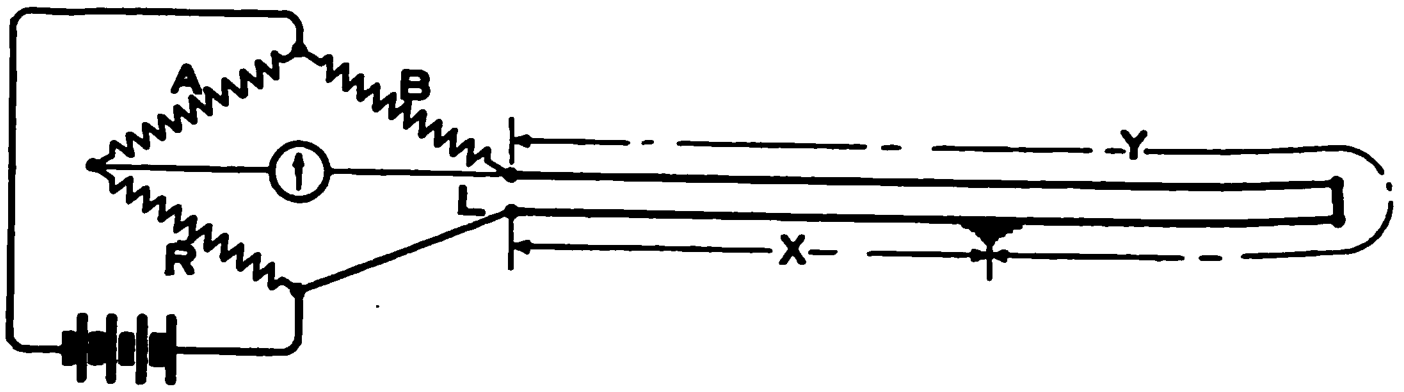

FIG. 1196.—First step: measurement of loop in "Varley" loop-test.

arm of a Wheatstone Bridge and the resistance of the loop is measured. Let this equal L. Next let the resistance of the grounded wire out to the grounded point equal X. Let the resistance of the good wire out the other distant end and back over the grounded wire to the grounded point equal Y. Then $X + Y = L$. The connections are then changed as shown in Fig. 1197. The only alteration is that the positive

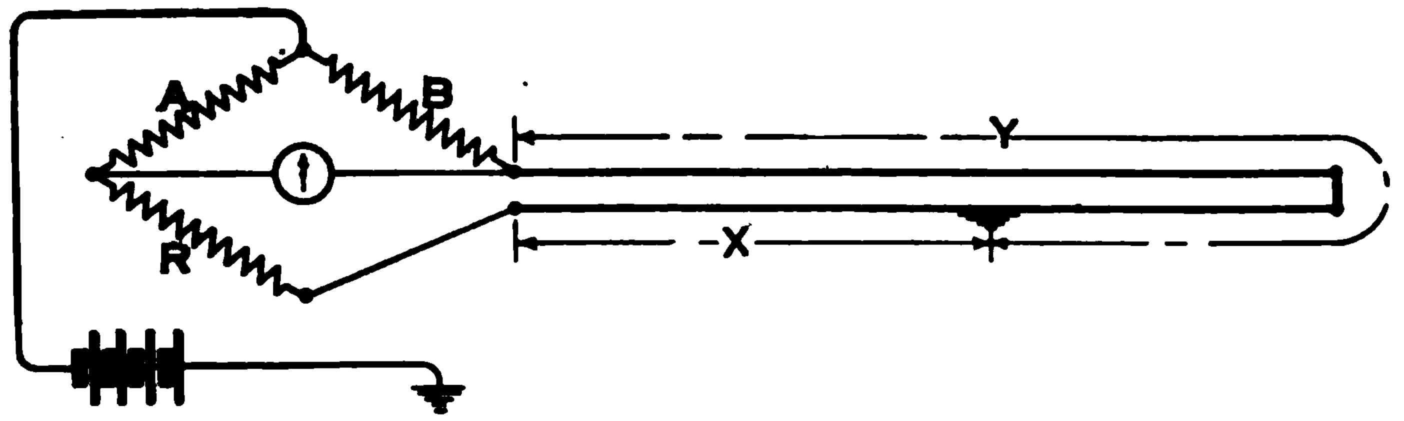

FIG. 1197.—Second step in "Varley" loop-test.

terminal of the battery is removed from the X binding terminal on the bridge and swung to the ground. This adds the portion of the grounded wire out to the grounded point in series with the R arm of the bridge and makes the unknown arm consist of the good wire and the remote portion of the grounded wire back to the grounded point. About 50 cells of battery are used to overcome the possible high resistance of the ground and the bridge should again be manipulated for a new balance. A balance will be obtained when:

$$A : B :: (R + X) : Y.$$

Then:

$$\frac{B \times (R + X)}{A} = Y. \tag{1}$$

As $X + Y = L$, $Y = L - X$.

Substituting this value of Y in equation (1), and clearing gives:

$$\frac{B \times (R + X)}{A} = L - X;$$

$$BR + BX = AL - AX.$$

Transposing:

$$AX + BX = AL - BR$$

$$X(A + B) = AL - BR;$$

$$X = \frac{AL - BR}{A + B}.$$

The value of L, in this equation, is obtained from the first test, and the values of A, B, and R, from the second test.

In a certain example the measurement of the loop gave a value for L of 32.8 ohms in the first measurement. Changing the connections for the second measurement a balance was obtained when $A = 1000$, $B = 100$, and $R = 253$. The cable was 8,000 feet long.

Applying the formula:

$$X = \frac{AL - BR}{A + B};$$

$$X = \frac{(1{,}000 \times 32.8) - (100 \times 253)}{1{,}000 + 100} = 6.81 \text{ ohms}.$$

This is the resistance along the bad wire to the ground. As the cable is 8,000 feet long, the length of the loop is 16,000 feet. $\frac{X}{L} \times D$ will therefore be the distance along the bad wire to the ground.

$$\frac{6.81}{32.8} \times 16{,}000 = 3{,}321 \text{ feet to ground}.$$

Sometimes the distance obtained by the calculation is greater than the resistance of one length of the cable. This is because the two wires entering the unknown arm of the bridge in the second test become crossed. In that case the distance obtained

is the distance out over the good wire and back over the bad wire to the grounded point.

The Murray Loop Test.—The Murray loop test is generally used on telephone cables. It is not considered quite as accurate as the Varley test, but is somewhat simpler in its final application.

The scheme is similar to the Varley and the first test for the measurement of the resistance of the loop is identical with the

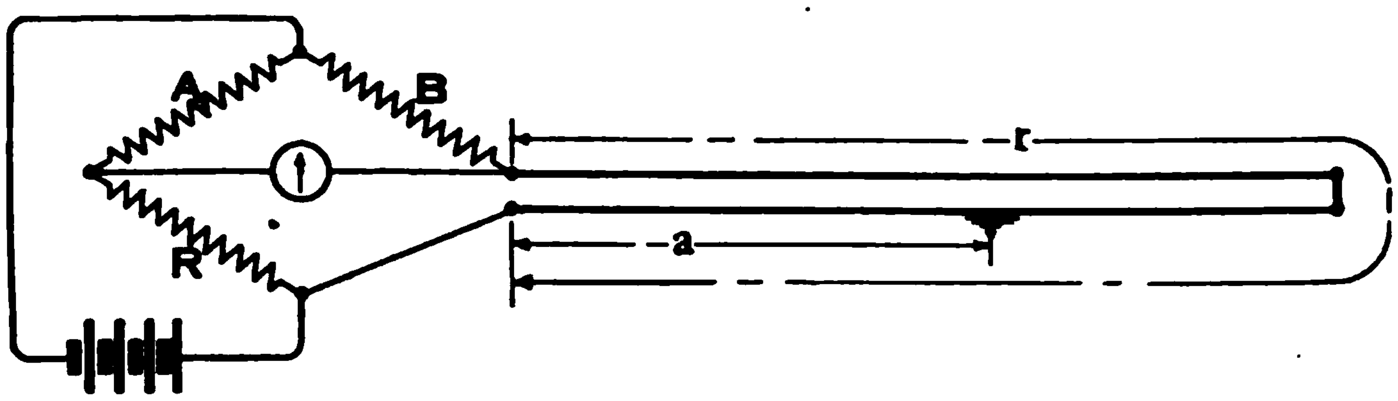

FIG. 1198.—First step in "Murray" loop test.

Varley. This is shown in Fig. 1198. Here the resistance of the entire loop is called r. The resistance of the bad wire out to the grounded point is a. The value of r is obtained by the expression:

$$A : B :: R : r.$$

The connections are next altered to those shown in Fig. 1199. This is radically different from the second Varley test. The B arm of the bridge is plugged up and not used. The connections

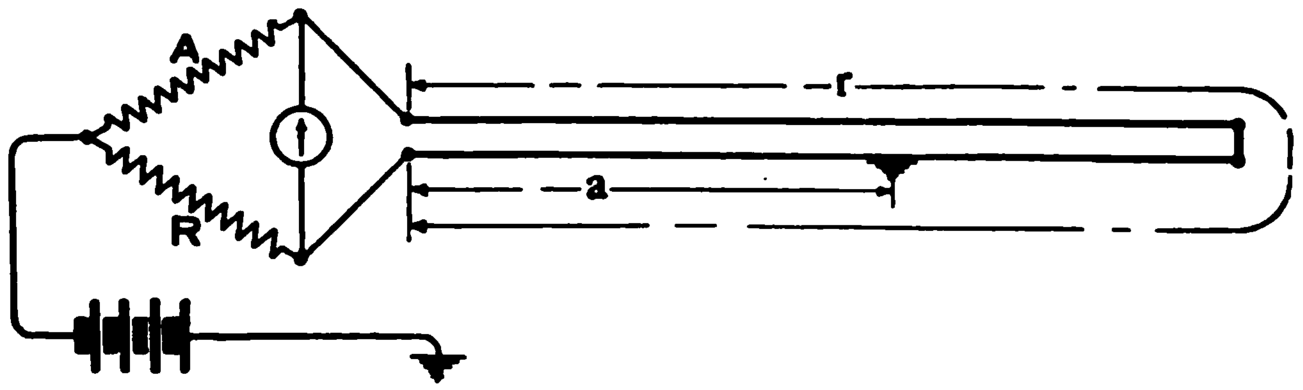

FIG. 1199.—Second step in "Murray" loop test.

of the galvanometer are altered as well as those of the battery. The theoretical arrangement is as shown in Fig. 1200. It will be observed that a is a **part** of r. r therefore includes both arms of the right side of the bridge. The proportion by which a is obtained will now be:

$$R : (A + R) :: a : r,$$

from which

$$\frac{R \times r}{A + R} = a.$$

Also $\frac{a}{r} \times D$ = distance in feet to the defect. Combining these expressions gives:

$$\frac{R \times r \times D}{(A+R) \times r} = \frac{R \times D}{A+R} = d = \text{distance to ground.}$$

It will be observed that when the two equations are thus combined the value of r, the resistance of the loop, is eliminated entirely and the first test may be omitted. Thus:

$$\frac{R \times r}{A+R} = a.$$

When r = resistance of loop in ohms.
a = resistance to ground in ohms.

and

$$\frac{R \times D}{A+R} = d.$$

When D = length of loop in feet.
d = length to ground in feet.

In a certain example the connections were made as in Fig. 1199 when $A = 100$, $R = 25$; with a cable 5,000 feet long giving $D =$ 10,000 feet.

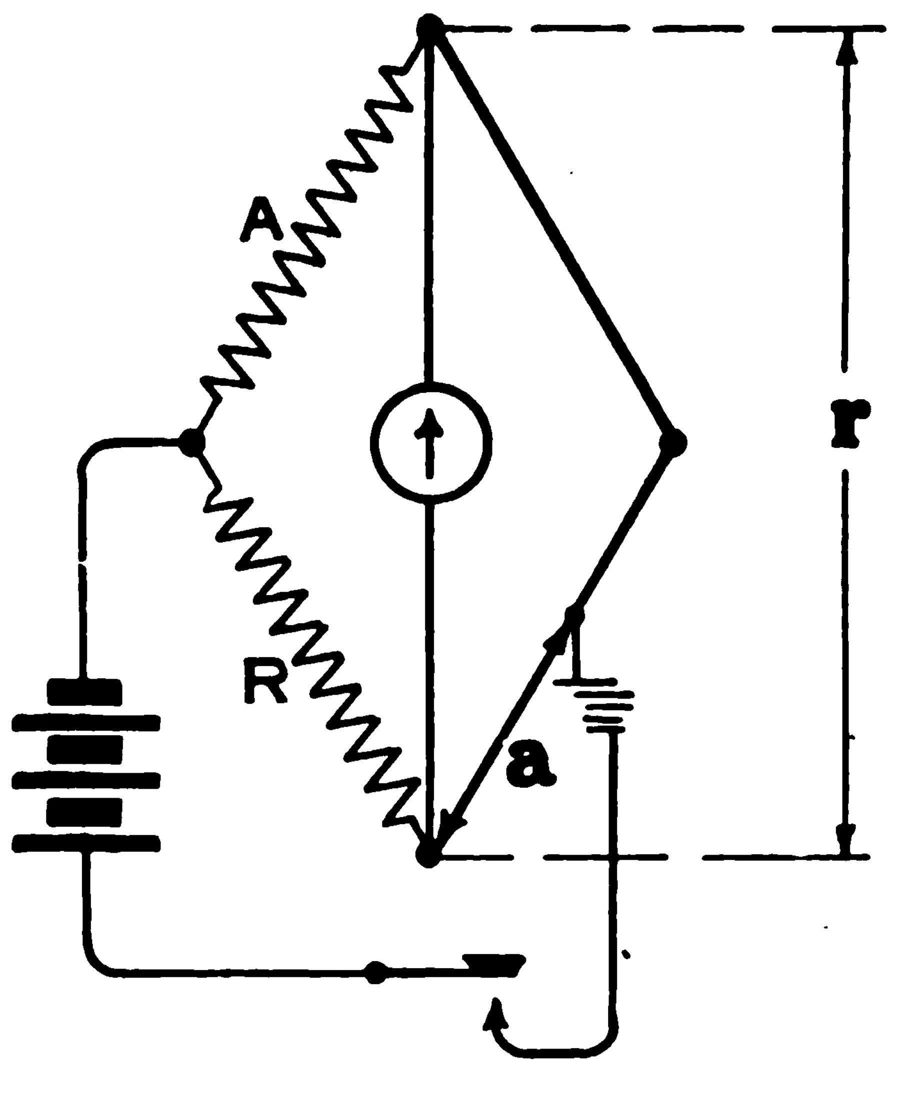

FIG. 1200.

Applying the formula:

$$\frac{R \times D}{A + R} = d;$$

$$\frac{25 \times 10{,}000}{100 + 25} = 2{,}000 \text{ feet to ground.}$$

The Scarlett Test.—The "Scarlett" test is a method of determining the resistance of a wire of unknown resistance B, which may be composed of several sections of different sizes, as for

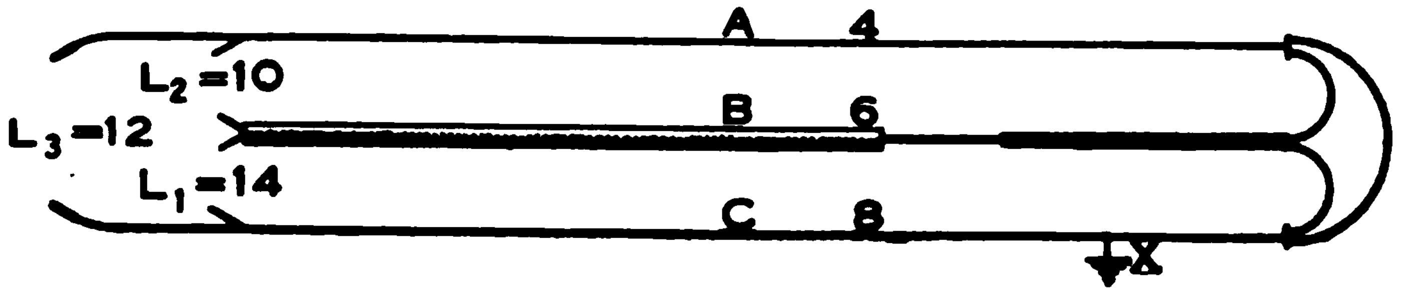

FIG. 1201.—"Scarlett" test.

example No. 19 in a cable under ground and No. 22 in an aerial cable. The object in determining the resistance of the wire is to permit the use of the Varley or Murray loop tests to locate the ground on a wire of uniform resistance at the point X, Fig. 1201. This could not be done without a knowledge of the resistance of the good wire to be used in connection with it to form a loop, because the wires B and C are not of **equal** resistance, and B is not of **uniform** resistance.

This test is performed by making three loop measurements. All three wires are connected together at the distant end of the

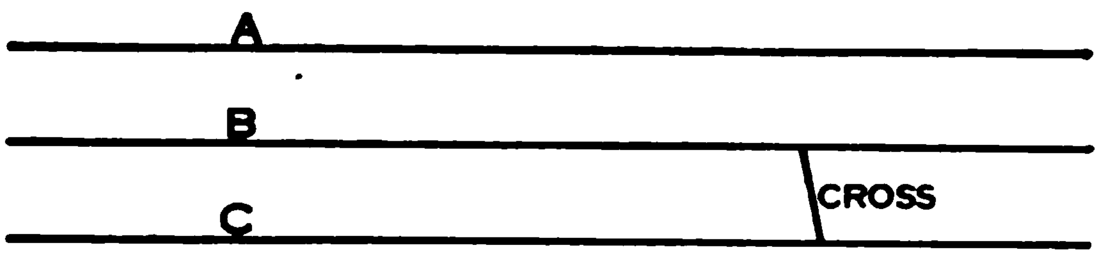

FIG. 1202.

cable. At the testing end a measurement is made first between A and B, second between B and C, and third, between A and C. Then: $L1 + L2 - L3 = 2B$.

To illustrate the application of this rule let it be supposed that A has a resistance of 4 ohms, B, 6 ohms and, C, 8 ohms. The loop measurements would then give $L1 = 14$; $L2 = 10$, $L3 = 12$.

Applying the formula will give $14 + 10 - 12 = 12$. As this is twice the resistance of the wire *B*, $\frac{12}{2} = 6$ ohms. This is the resistance of *B*. This wire may now be used in connection with *C* for a loop measurement, from which the location of the ground can be determined.

In Fig. 1202, a cross between wires *B* and *C* can be located by the Varley or Murray loop tests by using *C* as the ground and the defect as the grounded point on *B* where *A* is used as the good wire to form the loop.

SECTION XXII — CHAPTER VI

TELEPHONY

CABLE TESTING

1. Explain how a break in one wire of a pair in a cable may be located when a perfectly good pair of wires of the same gauge, in the same cable are available for comparison. Sketch connections and give formula.

2. In the above test, let *A* equal 100 ohms and *R* equal 648 ohms in a cable 5,300 feet long. What is the distance to the break?

3. In a similar test, *A* equals 100 ohms and *R* equals 273 ohms, when a balance is obtained on a cable 6,850 feet long. What is the distance to the break?

4. Explain the scheme of the Varley loop test in locating a ground on one wire in a cable when a good wire of the same size in the same cable is available for testing. Give formula.

5. In a Varley test, the resistance of the loop measures 46.5 ohms. In the second measurement a balance was obtained when *A* was 1,000 ohms, *B* was 100 ohms and *R* was 328 ohms. The cable was 6,400 feet long. Required the distance to the grounded point.

6. In a Varley test the resistance of the loop measures 24.6 ohms. In the second measurement a balance was obtained when *A* was 1,000 ohms, *B* 100 ohms and *R* was 416 ohms. The cable was 5,400 feet long. Required the distance to the grounded point.

7. Explain the scheme of the Murray loop test. What is its advantage over the Varley test? Give formula.

8. In a Murray loop test the value of *A* was 100 ohms and *R* was 48.2 ohms when a balance was obtained. The cable was 4,750 feet long. Required the distance to the grounded point.

9. In a Murray loop test the value of *A* was 100 ohms and *R* was 37.6 ohms when a balance was obtained. The cable was 6,250 feet long. Required the distance to the grounded point.

10. Explain the object of the Scarlett test. Give formula.

11. In a certain test to determine the resistance of wire *B* by the Scarlett method, the resistance of the loop consisting of *A* and *B* was 24 ohms, that of *B* and *C* was 26 ohms, and that of *A* and *C* 22 ohms. What was the resistance of *B*?

TELEPHONY

INSTRUMENTS FOR THE MEASUREMENT OF POTENTIAL AND RESISTANCE

If a voltmeter is placed across a cell of battery it indicates the delivered voltage and not the generated voltage. The delivered voltage is less than the generated voltage by the amount lost in the cell due to internal resistance. If two voltmeters, one of comparatively high resistance and one of comparatively low resistance, are used to measure the voltage of a cell of battery they may give different indications even though both are accurately calibrated instruments. This is because the larger current drawn by the voltmeter of lower resistance involves a larger

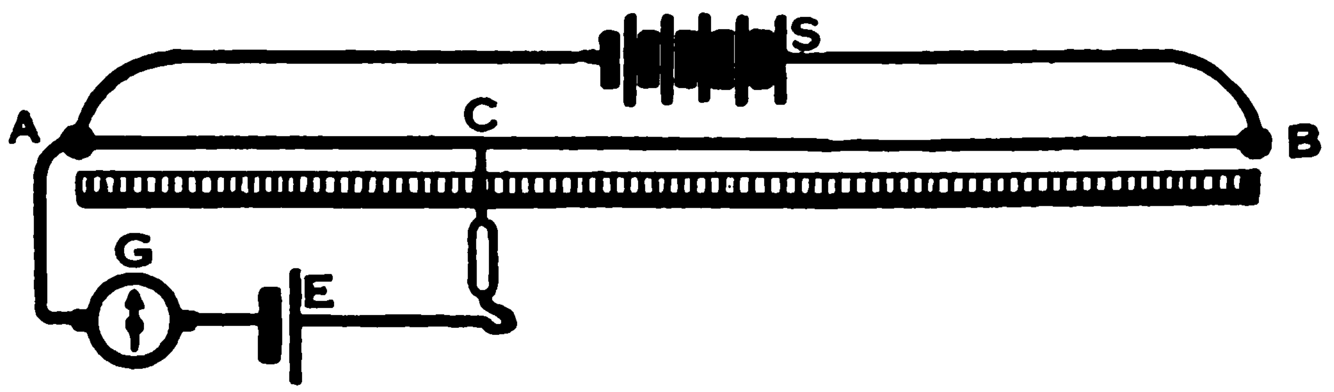

FIG. 1203.—Simple potentiometer.

drop in potential in the cell than the higher resistance voltmeter. An accurate indication of the actual voltage produced by the battery cannot therefore be readily obtained.

The Potentiometer

The potentiometer is a device for measuring the potential of an electrical source by comparing it with a standard source which does not require current to be passed through the source under test when its indication is obtained.

In its simplest form the potentiometer consists of a high resistance wire *A-B*, Fig. 1203, stretched over a uniformly divided scale of preferably 1,000 even divisions. Across the terminals of this wire is impressed the voltage of a storage battery *S*, preferably of five cells. The 10 volts produced by the battery falls uniformly through the slide wire from *B* to *A*. If the scale consists of 1,000 divisions, every 100 divisions will cor-

respond to one volt If now a cell of battery E is connected in series with a galvanometer and the terminal A of the slide wire, while the other terminal of the circuit is touched on the slide wire at C, it will be found that the current may or may not flow through E, depending upon the potential If the potential at the point C is higher than that of the battery E, current will flow from the slide wire into the branch circuit through E and G and the needle will deflect. If the potential of the point C is lower than that of the cell E, current will flow the other way from E to the point C and through the slide wire back through A and G This will cause the galvanometer to deflect in the opposite direction. It will be evident that there will be one particular point of balance where the potential at C on the slide wire is exactly equal to the voltage of the cell E against which it is balanced If E were a standard Weston cell giving 1 019

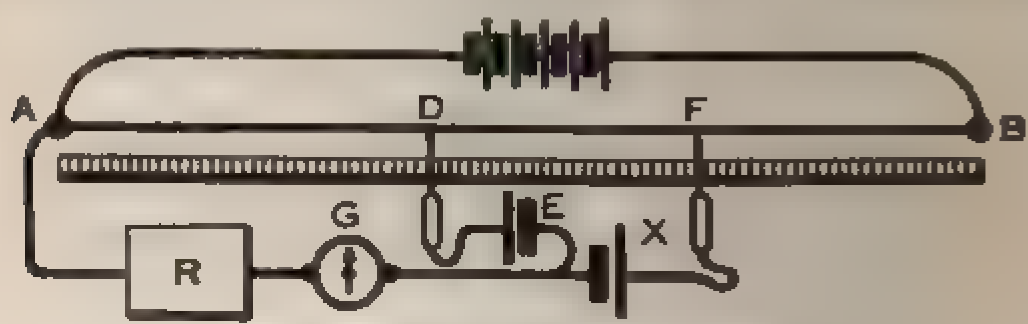

Fig. 1204 —Improved potentiometer.

volts, this point of balance would be 101.9 divisions along the scale from A The difficulty with this instrument in its crude form is that the storage battery's voltage is such that each scale division will not represent exactly $\frac{1}{100}$ of a volt.

An improved arrangement of the potentiometer is shown in Fig 1204. Here a storage battery is employed as before but the circuit, after passing through the galvanometer, branches from a standard cell E, to a cell of unknown voltage whose electromotive-force it is desired to ascertain The standard cell is balanced on the slide wire experimentally at the point D The cell X, whose voltage is unknown, is independently balanced at the point F When these two points of balance have been found, the voltage of the unknown cell may be calculated from the proportion:

$$E : X :: AD : AF$$

Where A-D and A-F represent the respective lengths of the resistance wire A-B and not their resistances.

It is therefore not necessary that the value of each division shall be exactly $\frac{1}{100}$ of a volt but only important that the voltage shall not have changed upon the terminals *A-B* between the time when the standard cell *E* is balanced at *D* and the cell *X* is balanced at *F*.

By using an extended scale or external volt-box, voltmeters may be calibrated by comparing them with a standard cell which gives the proportionate value for each division on the wire *A-B*. Fig. 1205 shows the actual diagram of connections

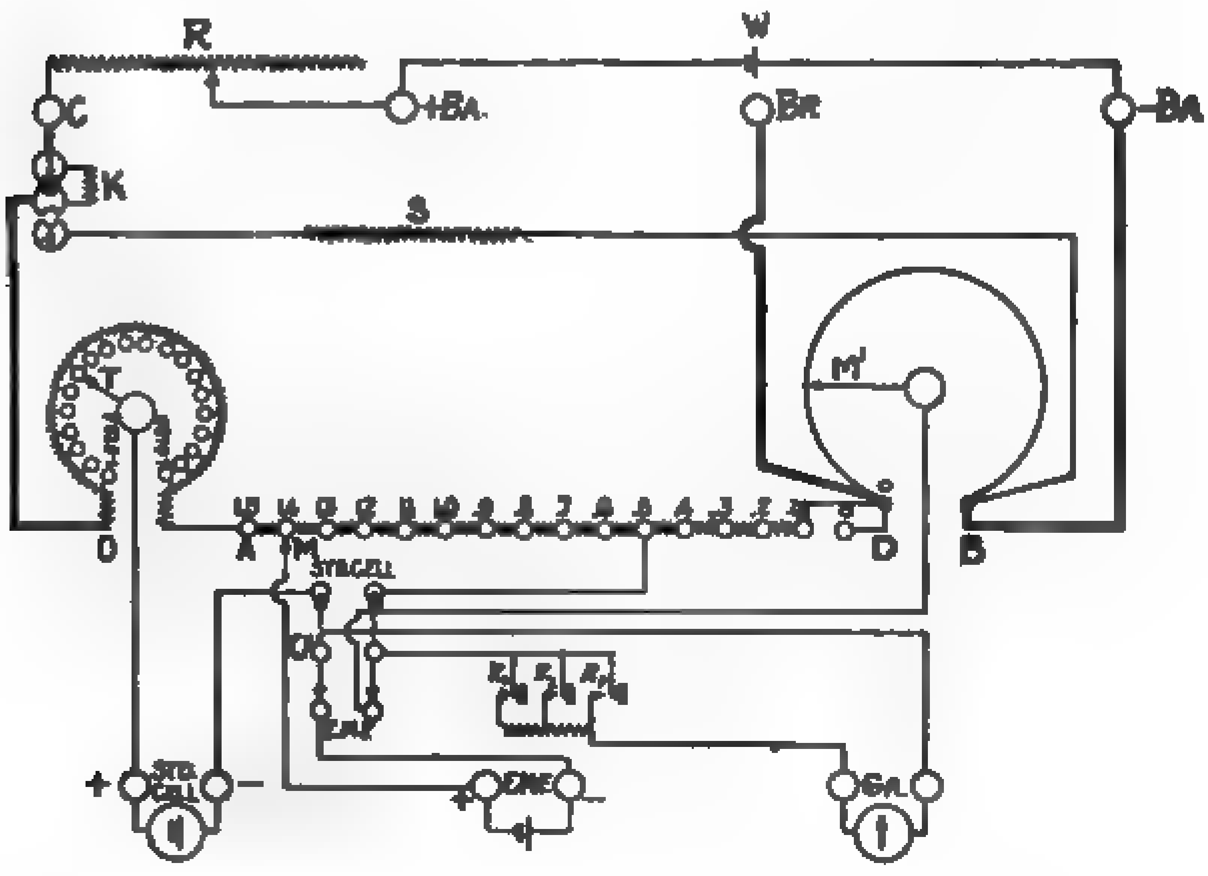

FIG. 1205.—Actual circuits in commercial potentiometer.

in a commercial form of potentiometer manufactured by The Leeds and Northrup Company. Ammeters may be calibrated by measuring the drop across a shunt of known resistance placed in series with the ammeter. Potentiometers are usually made to measure potentials up to and including 1.6 volts. If it is desired to accurately measure potentials higher than this a volt-box may be used. The connections of a volt-box as used in the calibration of a voltmeter are shown in Fig. 1206. Assuming that it is desired to calibrate the voltmeter at 150 volts, the voltmeter and the 150-volt terminals, *E* and *G* are connected across the source *C-D*. The terminals from *F-G* are connected

to the e.m.f. terminals of the ordinary potentiometer. The resistance of the volt-box between *F* and *G* is exactly one one-hundredth of the resistance between *E* and *G* and the drop at these points will be in direct ratio to the resistances. It is then

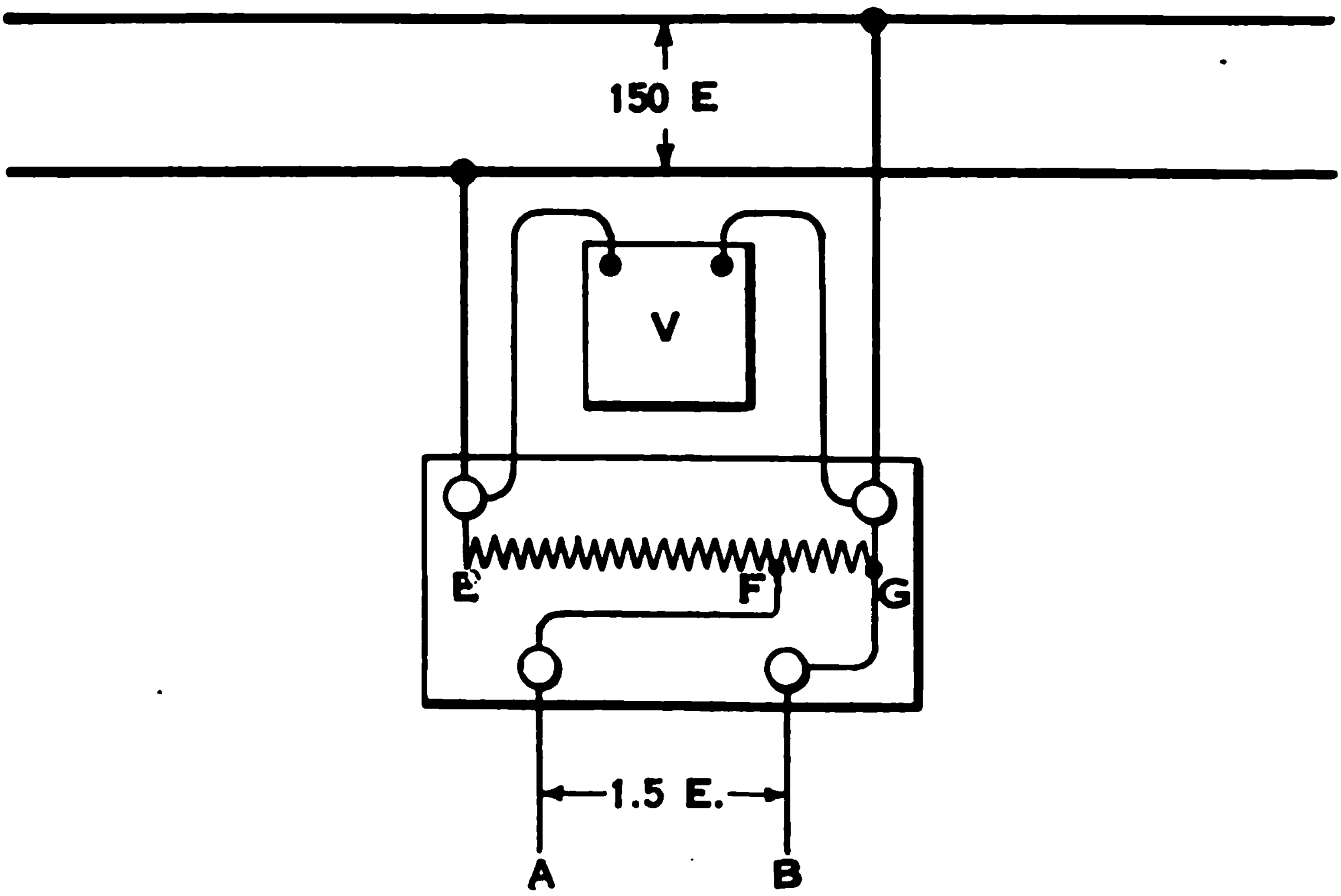

FIG. 1206.—Circuits in potentiometer for measuring voltage.

evident that when the potentiometer shows 1.5 volts at *A-B*, there must be exactly 150 volts at *E-G*. Similarly, multiplying the potential at *A-B* by one hundred will give the voltage at

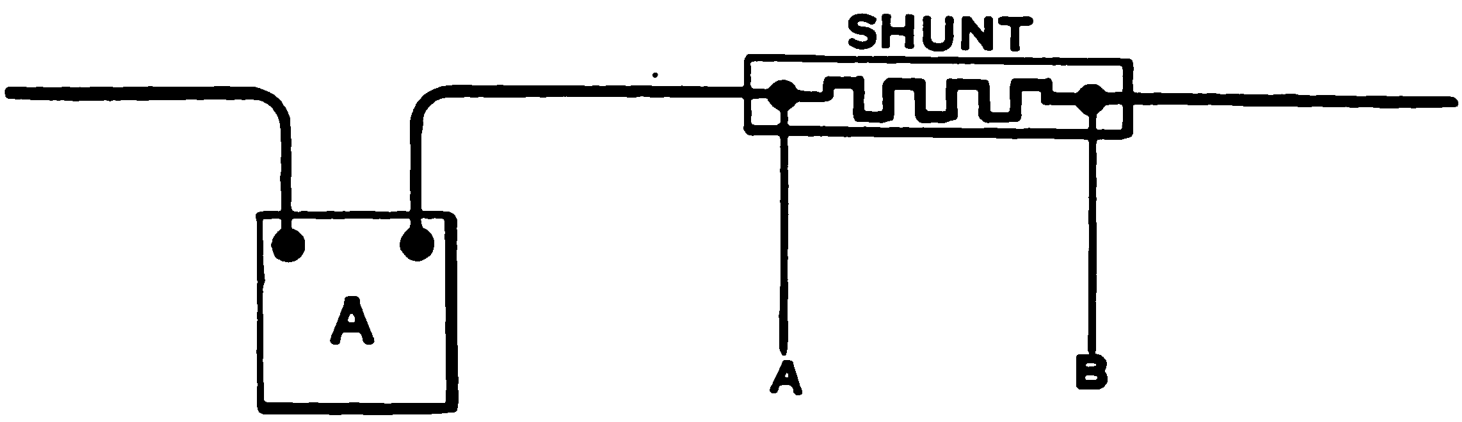

FIG. 1207.—Circuits in potentiometer for measuring current.

E-G for any value of line voltage less than 150. Volt-boxes may be made for any desired range.

Ammeters may be calibrated by connecting the ammeter in series with a standard shunt as shown in Fig. 1207. The drop across this shunt at *A-B* is measured by the use of a potentio-

meter and since the resistance of the shunt is known, the current passing through the ammeter may be readily calculated with great accuracy.

The Megger

When measuring very high insulation resistances it is not necessary to find the exact resistance. It is only important to know that the insulation is above or below a certain standard. A practical instrument for measurements of this sort is known as the **Megger.** It is so designed that the terminals may be connected across the insulation of any wire or cable and by turning a handle an approximate indication of the actual resistance is immediately shown

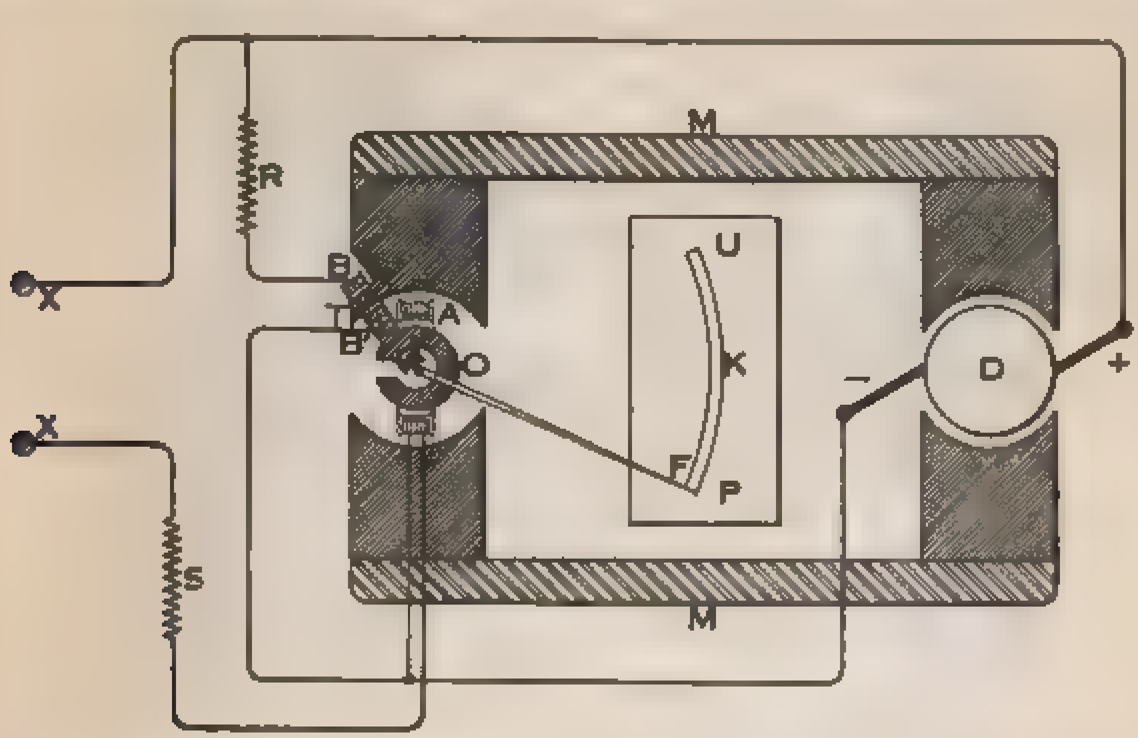

Fig 1208.—Magnetic circuits and electrical connections in "megger."

by the position taken by a needle on the scale. The principle of this instrument is illustrated in Fig 1208. *D* is the armature of a small direct-current generator, which, by means of an external handle, is geared to be rotated between the poles of permanent magnets *M-M* In a gap in the other end of these two bar magnets are two more soft iron pole pieces between which is fastened a soft iron cylinder, *O*, with a section cut away on the left. A coil of fine wire, *A*, called the current coil, surrounds this cylinder and is arranged to rotate on a vertical support Two other coils called the pressure coils *B-B'*, are rigidly attached to the same support One of these coils, *B'*, is arranged to thread itself over a section of the iron cylinder *O*, and the other

coil, *B*, surrounds a peculiarly shaped corner or horn of the soft iron pole piece *T*. Attached to the shaft which carries the three movable coils is a pointer *F*, which travels over the scale *K*. This shaft is supported in sapphire jewels. The general appearance of these coils, the manner of mounting, and the method of feeding current to them is shown in Fig. 1209. *R* and *S*, Fig. 1208, are resistance coils while *X-X* represent the terminals on the outside of the case to which the external resistance

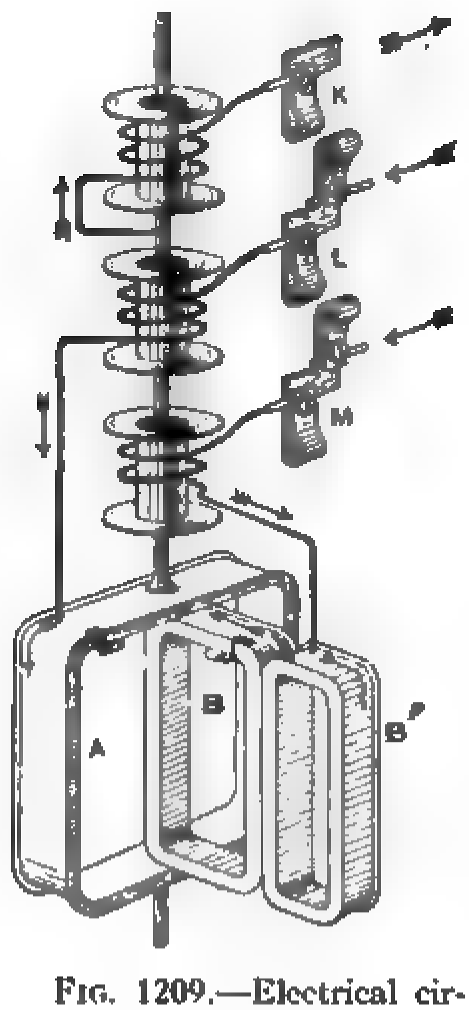

Fig. 1209.—Electrical circuits through coils of "megger."

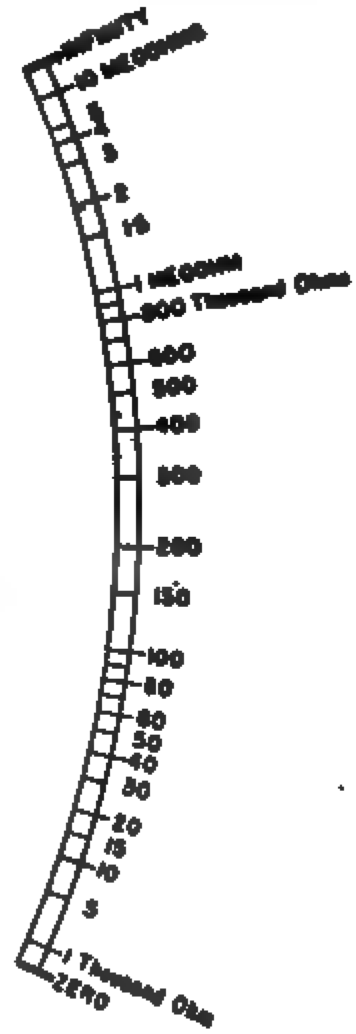

Fig. 1210.—Scale of "megger."

should be connected. Current from the generator armature has two paths open to it. One is from the positive brush and through the coil *R* and thence through the coils *B-B'* and back to the negative terminal of the generator. The other is directly through the resistance of the external circuit via *X-X*, back through *S* and the coil *A* to the negative side of the generator. The first path is through a closed circuit of unvarying resistance so that with a given e.m.f. the current therein is constant. On the other hand the current which the e.m.f. can maintain in the

other circuit is dependent upon the resistance between X and X, through the external insulation Current through the coils B-B' tends to oppose the permanent magnetism and these coils tend to move away from the iron cores which they surround into a position of weaker magnetic flux Current in the coil A tends to move the system in the opposite direction When current flows through both sets of coils at once, the two forces being in opposition, the entire system will take up a position dependent upon the relative strength of the currents in the two circuits. If the resistance across X-X is low, coil A becomes the stronger and the needle F remains on the P end of the scale. If the

FIG. 1211. –General appearance of "megger."

resistance externally is high, coil A becomes the weaker and the tendency of B-B' to move downward increases and the needle moves toward the U end of the scale The scale, Fig. 1210, is calibrated so that it reads the resistance in ohms across X-X directly. As a change in electro-motive-force and current affects both circuits alike, the readings are independent of the speed of the generator, which can be rotated by hand at any convenient speed. The e m f. of the generator is from 100 to 1,000 volts. The instruments are made with a range of from 0 to 10 megohms

with moderate voltage generators, and from 10 to 2,000 megohms with high voltage generators. It affords a simple and practical method of approximating with sufficient accuracy, the insulation resistance of any system. The general appearance of the complete instrument is shown in Fig. 1211.

SECTION XXII CHAPTER VII

TELEPHONY

INSTRUMENTS FOR MEASUREMENT OF POTENTIAL AND RESISTANCE

1. Explain the principle of a simple potentiometer. Sketch.
2. Explain the defect in the simplest form of potentiometer and show how it is overcome in the improved form. Sketch.
3. Explain how the potentiometer is used for calibration of a voltmeter. Sketch.
4. Explain how the potentiometer is used for the calibration of an ammeter. Sketch.
5. Explain the construction and principle of operation of the "Megger." Sketch circuits. For what kind of measurements is it particularly adapted?

TELEGRAPHY

SIMPLE TELEGRAPH SYSTEMS

The development of the electric telegraph, like most inventions, has been a gradual process. In 1821 Ampere suggested in Paris that a galvanometer be used for the transmission of signals according to a pre-determined code. In 1831 Joseph Henry used electro-magnets in New York for the purpose of transmitting signals read by audible sounds. In 1837 Samuel F. B. Morse developed the dot-and-dash telegraph system in which the signals were printed on a strip of moving paper. The same year Wheatstone in London, introduced the needle telegraph in which the electric signals were made visible at the re-

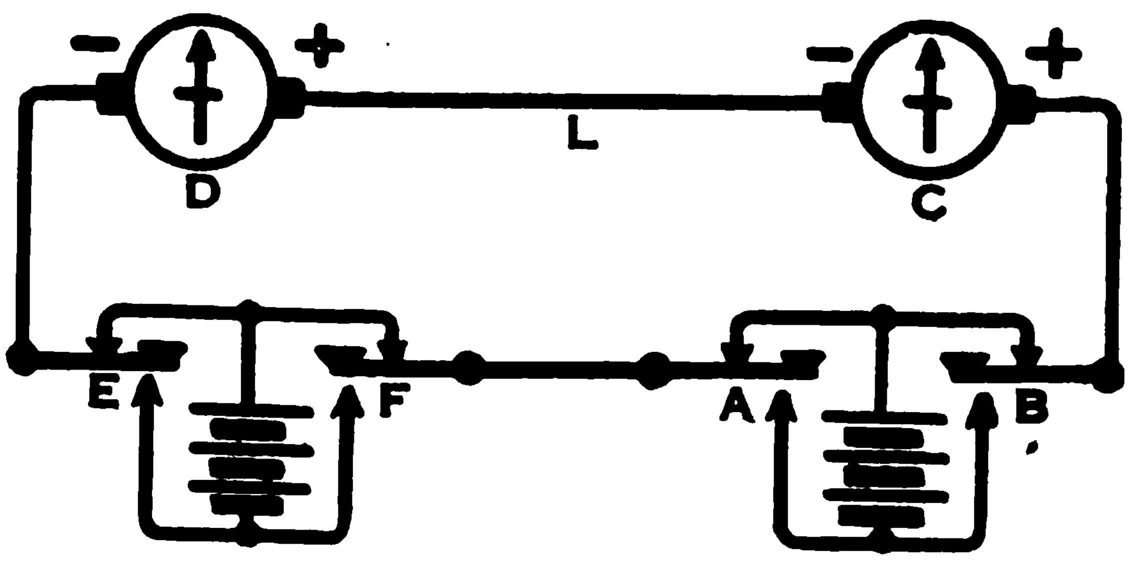

FIG. 1212.—Wheatstone needle telegraph.

ceiving point. In the same year Steinheil discovered that the earth could be used for the return of electrical currents so that only one wire would be required.

The Wheatstone Needle Telegraph

A simple form of the needle telegraph is illustrated in Fig. 1212. A galvanometer was mounted in an upright position with an index needle on its face moving between two stops. A battery and two double contact keys were employed with circuits to the distant instrument as shown. When the key *A* was depressed the negative side of the battery was connected to the lower wire or ground side, the positive side already being in circuit through the upper contact of key *B* with the instrument *C*, the line *L*, the distant instrument, *D*, the upper contacts of

the keys *E* and *F* and the return circuit. As the current went out through the home instrument to the line this was designated as a positive current. Should the key *B* be depressed the negative side of the battery was connected to line, the positive side being already in contact with the return circuit. This was called sending a negative current to line. The galvanometers deflected in the opposite direction. Deflections to the right corresponded to dots and to the left to dashes.

Early Morse System

The early Morse system employed telegraph type which was set in a frame and made contact between the terminals of an electrical circuit for a greater or less interval so that the trans-

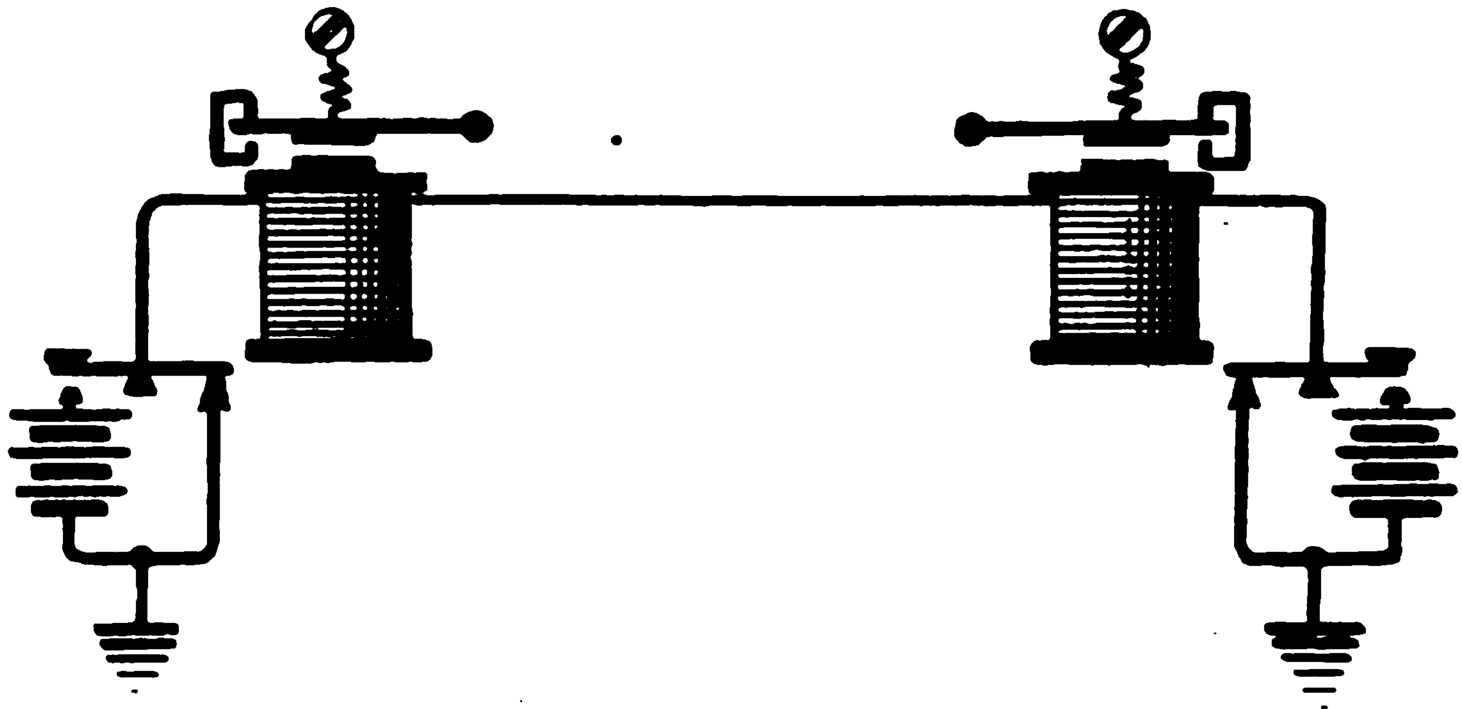

Fig. 1213.—"Open circuit" telegraph system.

mission was mechanical. A printing register was employed to print these signals upon a tape. The sending and receiving was thus made automatic. The original conception was that of a printing telegraph and there was no thought at that time of the possibility of sending by hand or reading by sound. Notwithstanding the strict regulations of the companies in the early days forbidding the receiving of messages by sound, operators very quickly came to understand the code and were able to distinguish between the forward movement of the armature and the back stroke, measuring the duration of the closure of the circuit, so that dots and dashes could readily be understood.

Open-Circuit System

The open-circuit system of telegraphy has been used abroad to a considerable extent; see Fig. 1213. The main electro-

magnets connect in series through a line circuit and the back stop on the keys with the ground. Pressing of the key at either end of the circuit sends a current through the line and both instruments in series. The batteries are both normally on open circuit.

Closed-Circuit System

In America the closed-circuit system shown in Fig. 1214 is preferred. Here a short-circuiting switch, *S*, placed normally around the contacts of the key is employed, so that it holds the line closed and the armatures on both instruments are held down. To send a signal, it is first necessary to open the short-circuiting switch, *S*, which releases both armatures. Depressing the key at the point where the switch was opened now energizes both

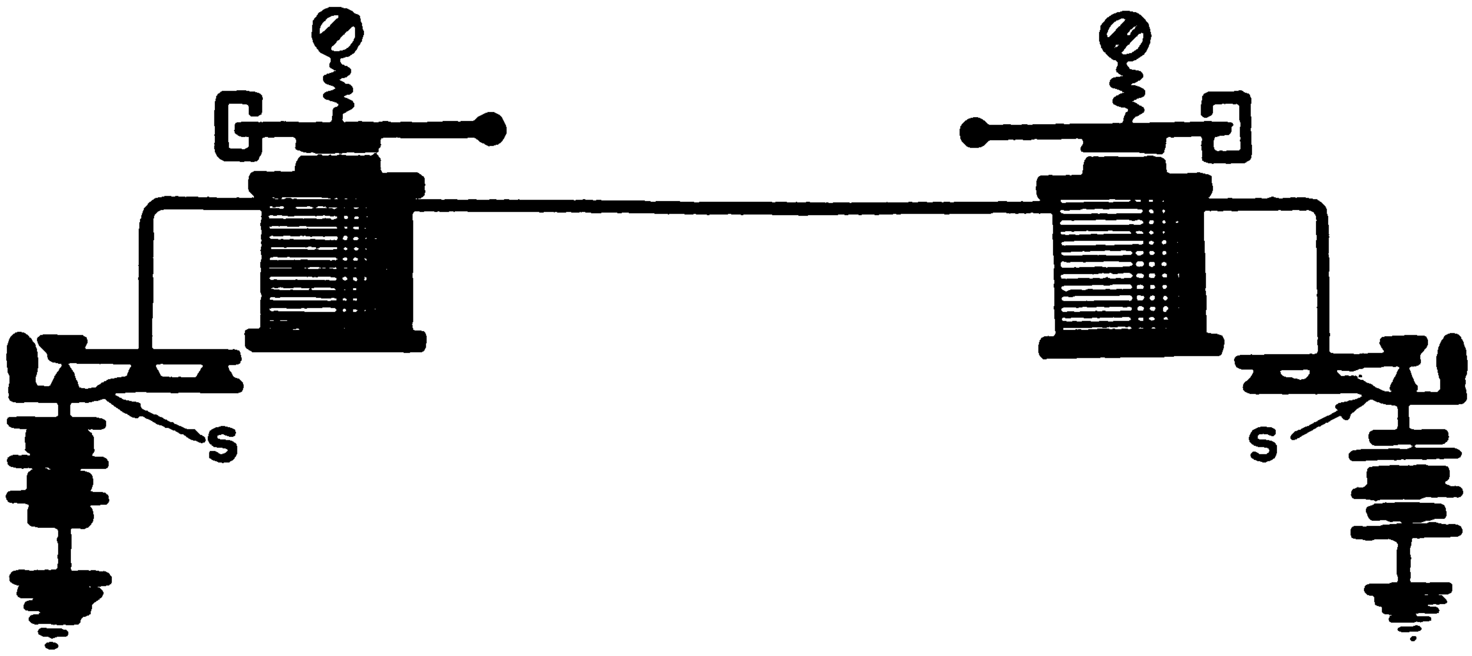

FIG. 1214.—"Closed-circuit" telegraph system.

instruments. When through sending, the switch, *S*, is again closed. The line may then be controlled from any other station by opening the switch, *S*, at that point and manipulating the key.

Use of Relays

To avoid the necessity of using a large current in the line, the main line instruments are wound for high resistance and a small current of from 20 to 80 milamperes under a considerable voltage, is passed through the circuit. Such a circuit is illustrated in Fig. 1215, which represents three stations. The main line relays *A*, *B* and *C* are wound for about 150 ohms each and the circuit is normally closed. It is an advantage to divide the batteries between the two ends of the line as shown, as this tends to minimize leakage. At every station the relay carrying the main line current is caused, upon its forward stroke, to close a

pair of local contacts *D-E* which permits a local battery *F*, consisting of three or four blue-stone cells, to send a current through a sounder *S*, wound for about 4 ohms resistance, thereby causing its armature to move in a vertical plane, striking a blow upon an anvil, thus giving a sharp sound. The impulse in the main line may be so feeble as to barely bring the contacts of the local circuit together but the impulse is thereby relayed into the local circuit where there is ample power to energize the sounder. The local circuit including sounder is duplicated at every station on the line. In large cities the local battery is omitted and the sounders are wound with a high resistance and designed to operate in series with another resistance directly upon the city electric light circuit.

The first Morse system was installed between Washington and Baltimore in 1843 and 1844 through an appropriation secured by

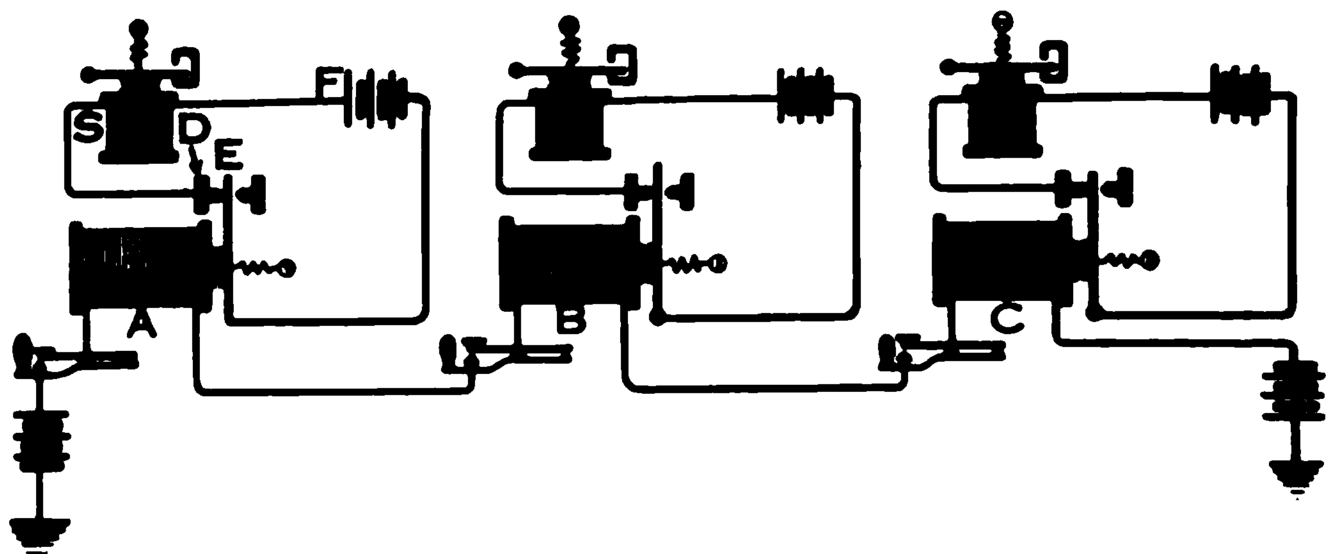

FIG. 1215.—"Closed-circuit" telegraph system for three or more stations, showing main and local circuits.

Morse from Congress of $30,000. The first message was sent over this line on May 27, 1844, and was taken from Numbers, 23d Chapter, 23d verse, and read: "What hath God wrought"? The first Morse relay weighed 180 pounds. The modern relay weighs about 2 pounds.

Types of Relays

Simple Relays.—There is a variety of relays. Those shown at *A-B-C* in Fig. 1215 are known as **simple relays** and respond to a current in **either** direction, **weak** or **strong.**

Polarized Relays.—Next in order comes the **polarized relay.** This responds to a current in **one direction only** but this current may be **weak** or **strong.** A permanent steel magnet with poles *N-S* as shown in Fig. 1216, has a soft iron electro-magnet mounted

upon it. A soft iron polar projection acts as an extension of the north pole so that the flux comes down to the point *N'*. A small spring, *B*, is employed to hold the soft iron tongue normally in the position shown. As the current flows through the coils in the direction of the arrows the poles of the electro-magnet become *S-N*. The action upon the tongue is to hold it definitely in the same position as that in which the spring pulls it. If, however, the current is sent in the reverse direction through the electro-magnets, the polarity of these poles is reversed. *S* is changed to *N* and *N* changes to *S*. This causes the tongue to swing from the position shown in full to the dotted position thereby closing the contacts of a local circuit between two wires *C-D*, which may be used to energize a sounder. The polarized relay may thus be made to respond to a current in one

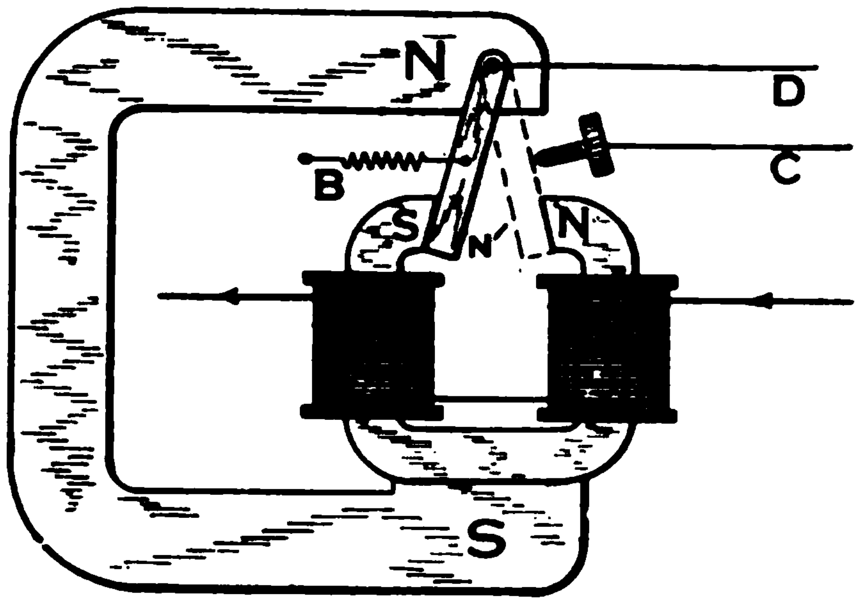

FIG. 1216.—Polarized relay.

direction only, while reverse currents have no effect upon it. It may also be used as a very sensitive simple relay by passing the current in the proper direction. A non-polarized relay requires that all of the magnetism employed in producing action shall be developed by the electric current. In a polarized relay a powerful permanent magnet is used to begin with, and on this as a fulcrum, a very feeble electric current may be made to produce a powerful result.

Neutral Relays.—A **neutral relay** consists of an ordinary simple relay in which the retractile spring has been set with sufficient tension to prevent the armature closing the local circuit, save with a **heavy current.** Such a relay responds to **currents** of **proper strength** in **either direction** but does **not respond** to a **weak current.**

Differential Relays.—The principle of the differential relay is shown in Fig. 1217. The electro-magnet M is wound with two coils side by side, A-A' and B-B'. These coils have the same number of convolutions and are situated the same relative distance from the core throughout. If A' is connected to B and the current admitted at the point C, it will pass in opposite directions through the two windings. If these currents are equal in amount the relay will be unaffected thereby. Yet if a current passes in either direction through one of the windings or in the same direction through both windings the relay will respond.

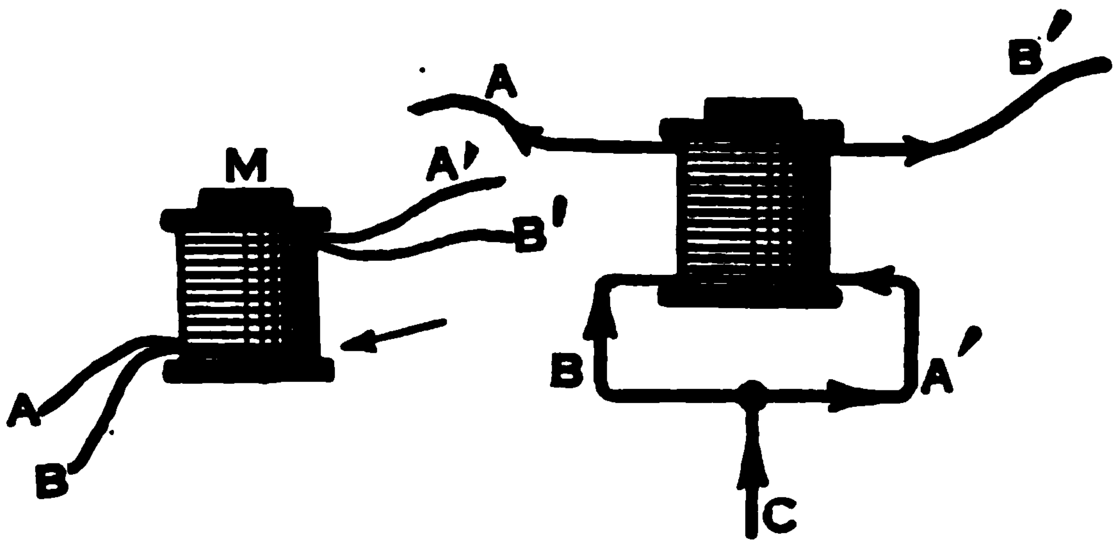

FIG. 1117.—Principle of differential relay.

Differential Neutral Relays.—The **neutral relay** which is a simple relay with a strong spring, may also be **differentially wound.** To operate it would now require that the current shall not only be of sufficient strength to overcome the retractile spring, but also that the current in one winding shall have a sufficient excess of strength over that in the other winding.

Differential Polarized Relays.—The **polarized relay,** which responds to a current in one direction only, may also be **differentially wound.** To operate it would now require that the current shall not only flow in the right direction, but that it shall also be of sufficient strength.

Summary.—For telegraphic purposes the various types of relays required may therefore be summarized as follows:

Simple relays,
Polarized relays,
Neutral relays,
Differential relays,
Differential neutral relays,
Differential polarized relays.

SECTION XXIII CHAPTER I

TELEGRAPHY

SIMPLE TELEGRAPH SYSTEMS

1. Explain the "Wheatstone" needle telegraph. Sketch.
2. Explain the "open-circuit" Morse telegraph system for two stations.
3. Explain the "closed-circuit" Morse telegraph system for two stations.
4. Explain the "closed-circuit" system for four stations, including main line, relays, keys and local sounders and batteries.
5. Explain the principle and operation of a simple relay. Sketch.
6. Explain the principle and operation of a polarized relay. Sketch.
7. Explain the principle and operation of a neutral relay. Sketch.
8. Explain the principle and operation of a differential relay. Sketch.
9. Explain the principle and operation of a differential polarized relay. Sketch.
10. Explain the principle and operation of a differential neutral relay. Sketch.

TELEGRAPHY

DUPLEX TELEGRAPHY

Duplex telegraphy is a system by which two messages, one in each direction, are sent simultaneously over one wire. The scheme was originated by Edison. Now it must be borne in mind that **two currents cannot** be sent simultaneously in opposite directions over one wire, and yet **two messages may be** thus transmitted.

The Differential Duplex

There are a number of duplex systems. The simplest is the differential duplex illustrated in Fig. 1218. This consists of a

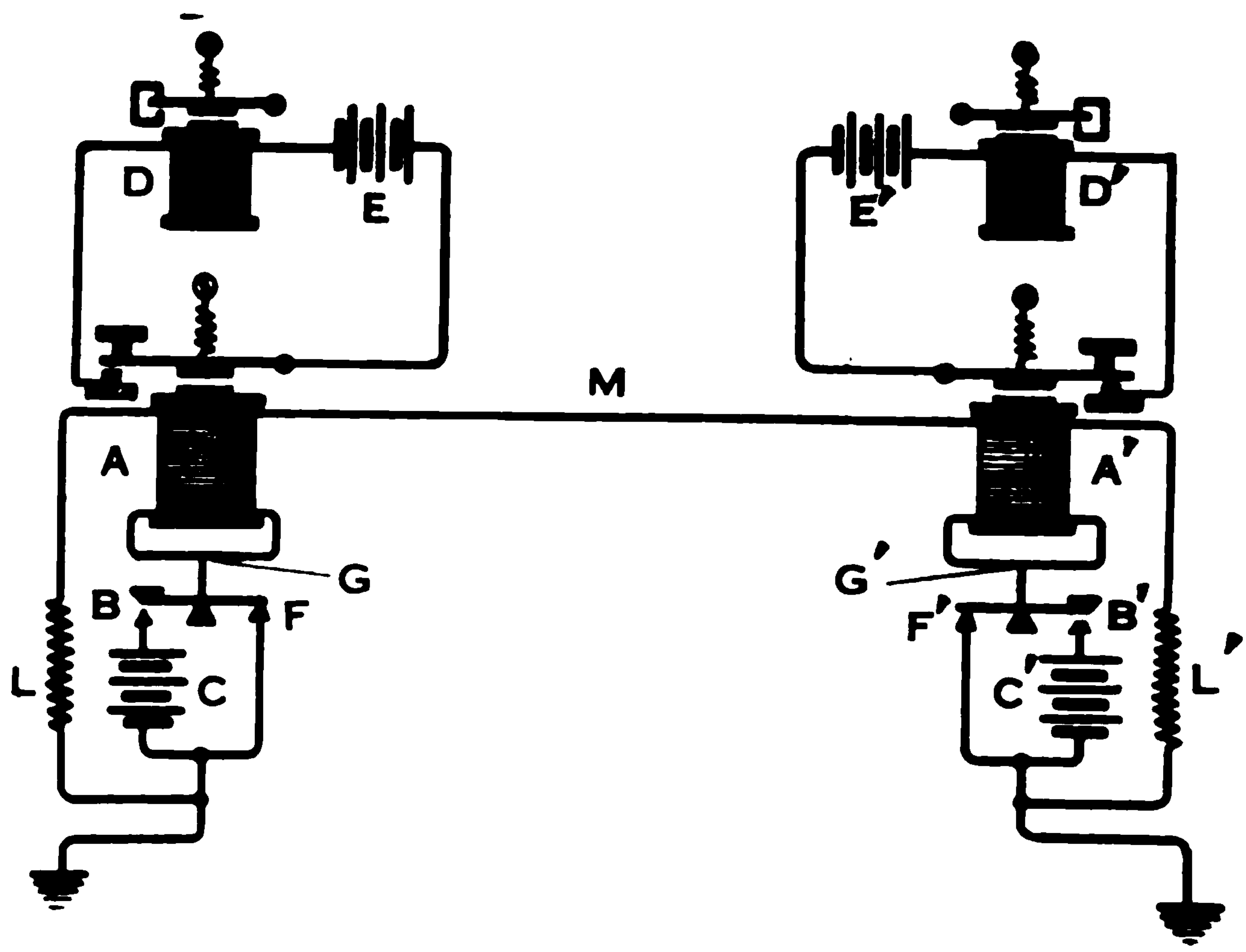

Fig. 1218.—The differential-duplex telegraph system.

differentially wound relay A, with a double contact key B, and a battery C, an artificial line L, and a local circuit comprising a sounder D and a local battery E. This apparatus is duplicated at the distant station. When the key B is closed, the battery C, normally on open circuit, sends current up to the point G, where it divides. The resistance of the artificial line L is so adjusted that together with the resistance of one winding of the relay, A, it will exactly equal the resistance of the other winding of this relay, the main line M, one winding of the distant relay, A',

and the ground return. Currents from the battery, *C*, are therefore divided equally and *A* will not respond to any outgoing currents, directed by the key *B*. When the current which passed through the main line, however, reaches *A′*, it passes around one winding of this relay only, and returns through the back stop *F′*, of the key *B′*, and thence through the ground to battery *C*. This relay therefore responds and closes its contacts and the local battery *E′* energizes the sounder *D′*. In a similar way *B′* can be made to energize relay *A*. It will thus be seen that each key can affect the distant station without affecting its own. It only remains to show that if both keys, *B* and *B′*, are simultaneously depressed, both relays will respond. This is actually the case. Assuming both of these keys to be depressed, the currents rise from both batteries *C* and *C′* but the voltages of these two batteries being equal and opposed to each other in the main line *M*, no current flows through one winding of each relay but current is free to flow through the other winding of each relay and return via the artificial lines *L*-*L′* to the battery in which this current originated. Thus both relays will be affected and both sounders will respond. Now it may be claimed that each man's **key** actuates his own relay but this is not the case. It is true that the **current** from the **home** battery affects the **home** relay, but this current is **deflected through** the **home** relay by means of the opposing electro-motive-force introduced into the line by the **distant key.** The artificial lines must include not only resistance, but also capacity to balance the main line in every way.

The Bridge Duplex

A more sensitive duplex system is the bridge duplex shown in Fig. 1219. Here the double contact key is used as before, but the circuits resemble those of a Wheatstone Bridge. The relay *A* has but a single winding and is very sensitive. In fact a polarized relay used as a simple relay may be employed in this position. The key *K*, when depressed, causes current to enter the bridge at the point *F*, where it divides through two ratio arms *B* and *C*. The artificial line is shown at *L*. Now the ratio arms *B* and *C* are manipulated and the artificial line is adjusted until the ratio of *B* to *C* is the same as the ratio of *M* to the entire resistance of the distant station. When this proportion has been established, there will be an equality of potentials at the points *D* and *E* and no current will flow through the

relay A. Thus current may be sent to the main line without disturbing the home relay. It will be observed that this system depends upon an **equality of potentials,** while the preceding system depended upon an **equality of currents** for the non-action of the home relay.

The current which passes through the main line reaches the point D' and divides, part of it going down through the relay A' and thence through the artificial line L' to the ground and back, thus affecting the relay A'. A portion of the current is shunted around through B'-F'-C'. A small resistance R-R' is inserted in the circuit including the back stop of each key to prevent short circuiting the battery during the period when the

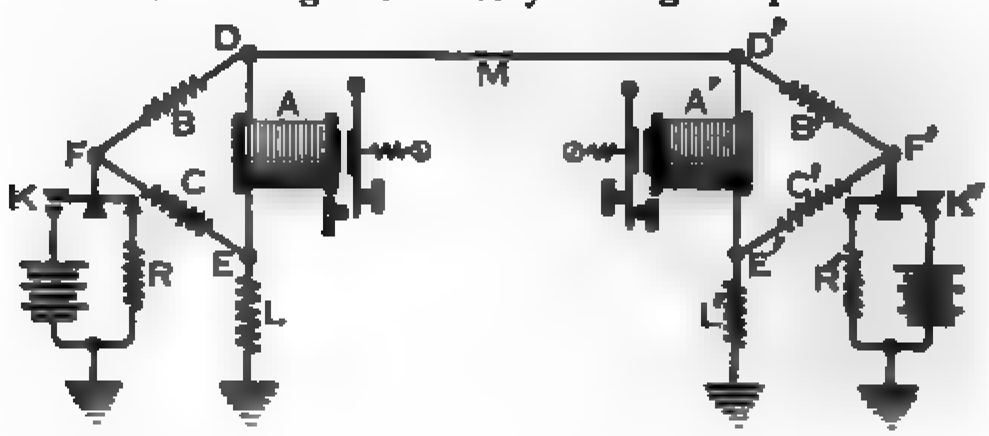

Fig. 1219.—The bridge-duplex telegraph system.

front stop of the key is closed before the back stop opens. The actual keys which are employed are not as crude as those illustrated. The mechanism actually used is called a **transmitter** and will be described later.

As in the preceding system the key K', can actuate the relay A. Duplex operation will, as before, be possible provided both keys can actuate both relays simultaneously. Suppose that keys K and K' are both closed. Current from the two batteries rises through K-F-B, in the one station and K'-F'-B' in the other station. As these currents are urged by equal and opposite electro-motive-forces they oppose each other in the main line and are deflected at one station through D-A-E-L and at the other station through D'-A'-E'-L'. This will cause both relays to respond, as in the previous system, each relay being actuated by current from the home battery, but under the direction of the key at the distant station.

The Polar Duplex

The polar duplex system employs differentially wound polarized relays. The elementary circuits are shown in Fig. 1220.

Two sources of current are employed at each end of the line These may be either batteries or generators of equal potential. A **pole changing key** provides a circuit with one source normally closed through main and artificial lines When the key is operated the polarity of the source is simply reversed The armatures of the relays are soft iron extensions from permanent magnets not shown. They are therefore permanently magnetized With the circuits normally as indicated, one battery at each station is connected with its positive terminal to the ground. These two electro-motive-forces, being equal and opposite in direction, do

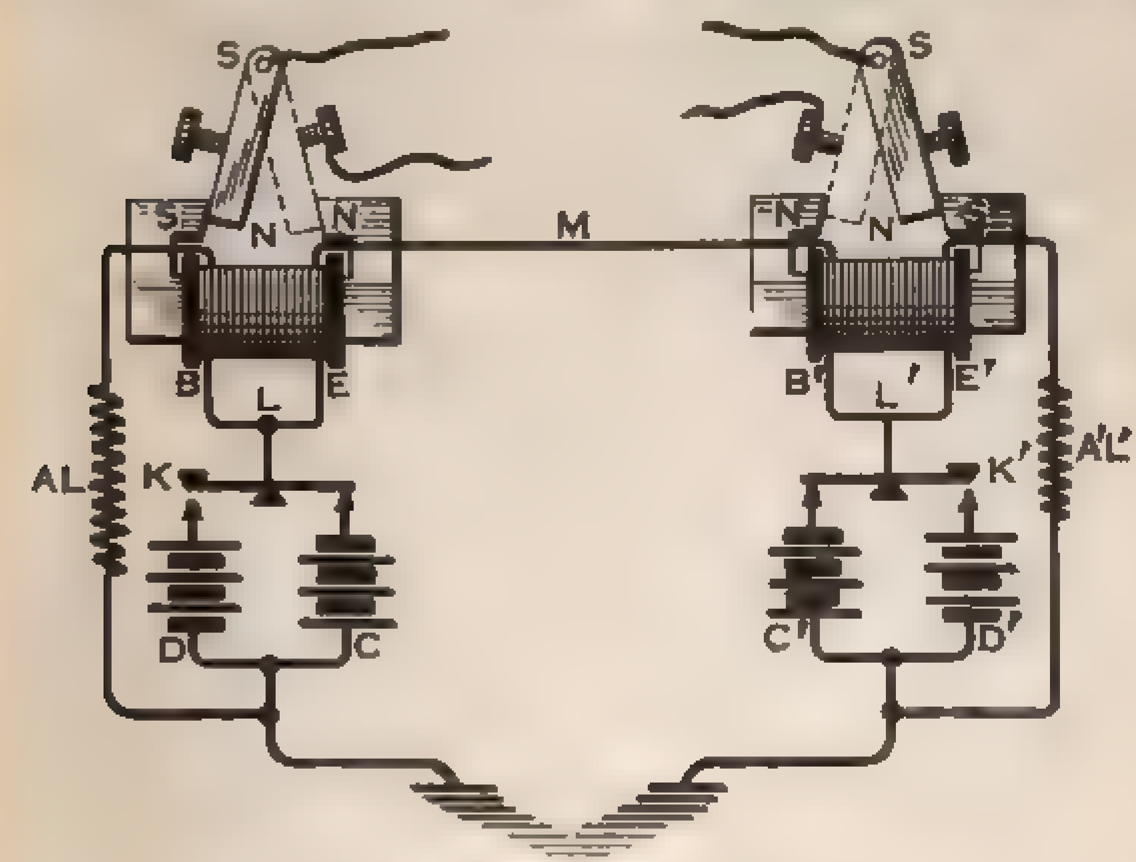

FIG. 1220.—The polar-duplex telegraph system.

not send any current through the ground or main line M. A circuit is provided, however, by which the current can flow from each source to the artificial line A-L at one station, and A'-L' at the other station, thence through one winding of the relay and through the back stop of the key to the battery in which it originated. These currents are in such a direction as to produce the polarity indicated in the figure and retain the armatures on the dead stops. Should the key K be depressed, the polarity of this source is reversed. The positive side of the battery D is connected to the line and the negative side to the ground Assuming

the source to have an e.m.f. of 40 volts, current rises to the point *L* and divides, one portion under 40 volts goes through the relay at the home station and passes down through the artificial line and back to the battery. The other portion goes differentially with respect to the first current, through the other winding of the relay and thence to the main line. As this current is in series with the battery of 40 volts at the distant station, the total pressure in the main line circuit is 80 volts. This produces a current twice as strong as the one in the artificial line and therefore the tendency to hold the armature on the dead stop in the home relay is twice as strong as is the tendency of the current which passed through the artificial line to throw it over on to the live stop. After passing through the main line the current comes down through the winding B' under a pressure of 80 volts and passes in series through the battery C' and returns through the ground to the battery D. At the same time battery C' is sending a current up through the artificial line A'-L' and down through the winding E' of this relay. The currents in B' and E' are differential with respect to each other. The one in B', tending to move the armature on to the live stop, is under a pressure of 80 volts, while the one in E', tending to hold the armature on the dead stop, is under a pressure of 40 volts. The closing tendency for this relay is therefore twice as strong as the tendency to remain open, and the relay closes. In a similar way pressing key K' would actuate relay B-E while not affecting relay B'-E'. If keys K and K' are both depressed at once, the direction of current in one winding of each relay is reversed. This throws both armatures on the live stops and the impulse is relayed into the local circuits and sounders. It must be observed as before that while in this instance the source of current for actuating the home relay is located at the home station, nevertheless the **actuating impulse** which **directs** the current into the **home relay** is the **key** at the **distant station.**

The Principle of Diplex Operation

Diplex telegraphy is a scheme for sending two messages simultaneously in the same direction over one wire. While this principle is not embodied in a system by itself, it forms the foundation of the quadruplex system and will therefore be explained. The plan involves the use of two distinct types of relays which respond under two separate conditions, neither one of which

conflicts with the other. Relay *A*, Fig. 1221, is a **simple polarized relay,** responsive to current in **one direction** only, but this current may be weak or strong. Relay *B* is a **neutral relay** responsive to a **strong current only** in **either direction.** Relay *A* is governed

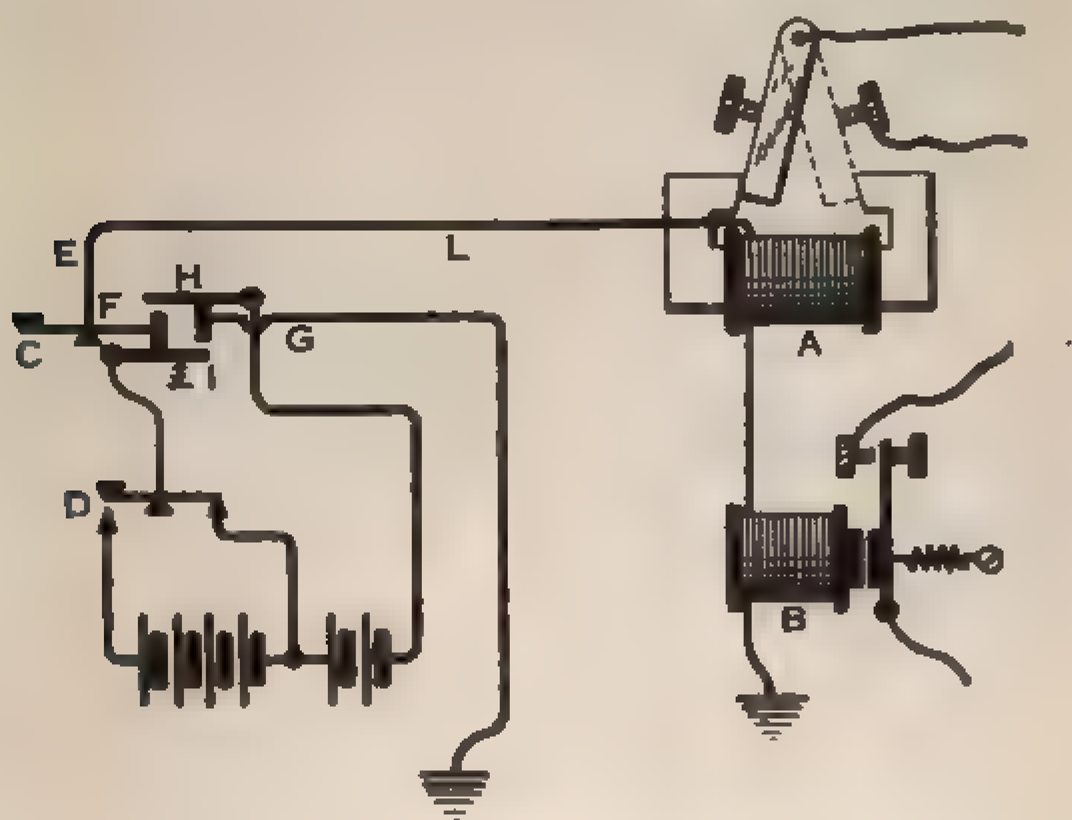

FIG. 1221.—Principle of diplex telegraphy.

by the **direction** of the current **regardless** of its **strength.** Relay *B* is governed by the **strength** of a current **regardless** of **direction.** *C* is a **pole-changing key** which governs the **direction** of current **only,** in the line *L*. *D* is a key which governs the **strength** of the **current only.** When neither key is depressed current under pressure of approximately 40 volts passes through the back stop of key *D*, thence through key *C* to line *L*, through relays *A* and *B*, back via the ground, upper contact *H*, to the battery. This current is in such a direction as to hold the polarized armature of *A* on the dead stop. It is so weak that it does not overcome the tension of the retractile spring on *B*, therefore the armature of this relay remains on the dead stop. If key *C* is depressed the connections are altered to those shown in Fig. 1222. Contact *F*

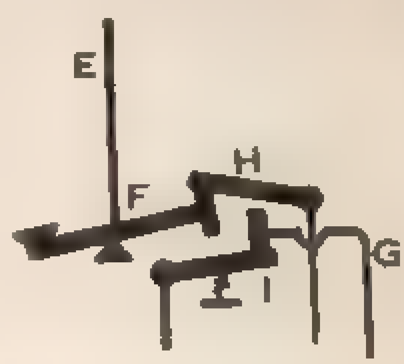

FIG. 1222.—Principle of pole-changing key.

rises, closing the circuit through H, to the negative side of the battery and breaking H from the ground G. At the same time I connects the positive side of the battery to G and ground. Thus, the operation of this key simply reverses the connections of the 40-volt battery with respect to line and ground. Actually a pole-changing transmitter, to be explained later, is employed. The current therefore flows through the ground circuit and back up through B and A, returning via contacts E-F-H to the 40-volt battery. This reversed current, being of small amperage, does not affect B, but its **direction** is such as to throw the armature of the polarized relay A over onto the live stop. Thus C controls A. If key D is depressed, current from the 100-volt battery plus the 40-volt battery is sent via line wire L or via ground wire G, depending on the position of key C, through the circuit including both relays. This, being a strong current, will actuate relay B. If its direction is via L it does **not** actuate relay A, but if key C is depressed this current is directed via the ground. Thus if both keys are depressed at once, a strong current is directed to ground via G passing up through B, where its **strength** is sufficient to actuate this relay, thence through A where its **direction** is such as to actuate this relay, returning via L and F-H, to the battery. Thus each key controls its own relay and both keys affect both relays

The Edison Reverser.—A certain condition which arises must now be considered. Suppose that while key D was depressed, and a strong current was flowing via L down through A and B, thereby actuating B, key C should be depressed. This would mean a reversal of heavy current in the line. While the current was passing through zero, the magnetism in B would fall to zero. At this instant, the armature of B would be released. Thus if D was sending a dash to B and in the middle of this dash the key C was depressed, the reversal of the current would make a break in the dash on B for reasons just explained. To avoid this contingency, Edison developed the **Reverser,** shown in Fig. 1223. Here the main line L is led through relay B, which is the same as relay B in Fig. 1221. The local contacts, however, of this relay are reversed, the live contact being the back stop and the dead contact the front stop. The local circuit comprises another relay C, called a **reverser,** and a local battery. This relay also has its contacts reversed, the back stop being alive and the front

stop dead The sounder D and its local battery are in the local circuit from this relay. Now assume as before that, due to the closing of the pole-changing key, there is a reversal of current in relay B. Normally the armature is closed against the dead stop E. When the current reverses in B, the armature is momentarily released, but as the contact F is some distance back,

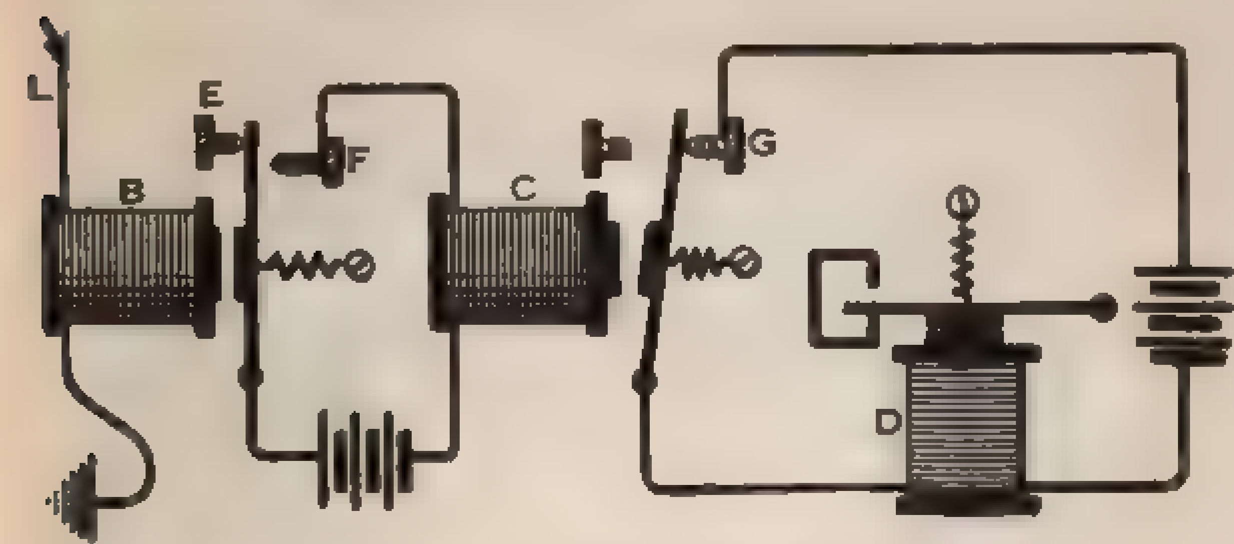

FIG. 1223.—The Edison reverser.

the armature does not have time to reach it before the flux in B picks up again and the armature is drawn forward. If the armature does not reach F, the circuit on C is not closed. If C carries no current, the contact G on the live back stop of this relay is not broken and the local circuit comprising the sounder D remains closed. Therefore a complete reversal of current may occur in B without the circuit being opened on the sounder D.

SECTION XXIII CHAPTER II

TELEGRAPHY

DUPLEX TELEGRAPHY

1. Sketch and explain the principle of the "differential duplex" telegraph system.
2. Sketch and explain the principle of the "bridge duplex" telegraph system.
3. Sketch and explain the principle of the "polar duplex" telegraph system.
4. Sketch and explain the principle of the "diplex" telegraph system.
5. Sketch and explain the principle of the Edison reverser.

TELEGRAPHY

QUADRUPLEX SYSTEMS

The quadruplex telegraph system involves the sending of two messages in each direction, making four messages in all, simultaneously over one wire. This requires two sending and two

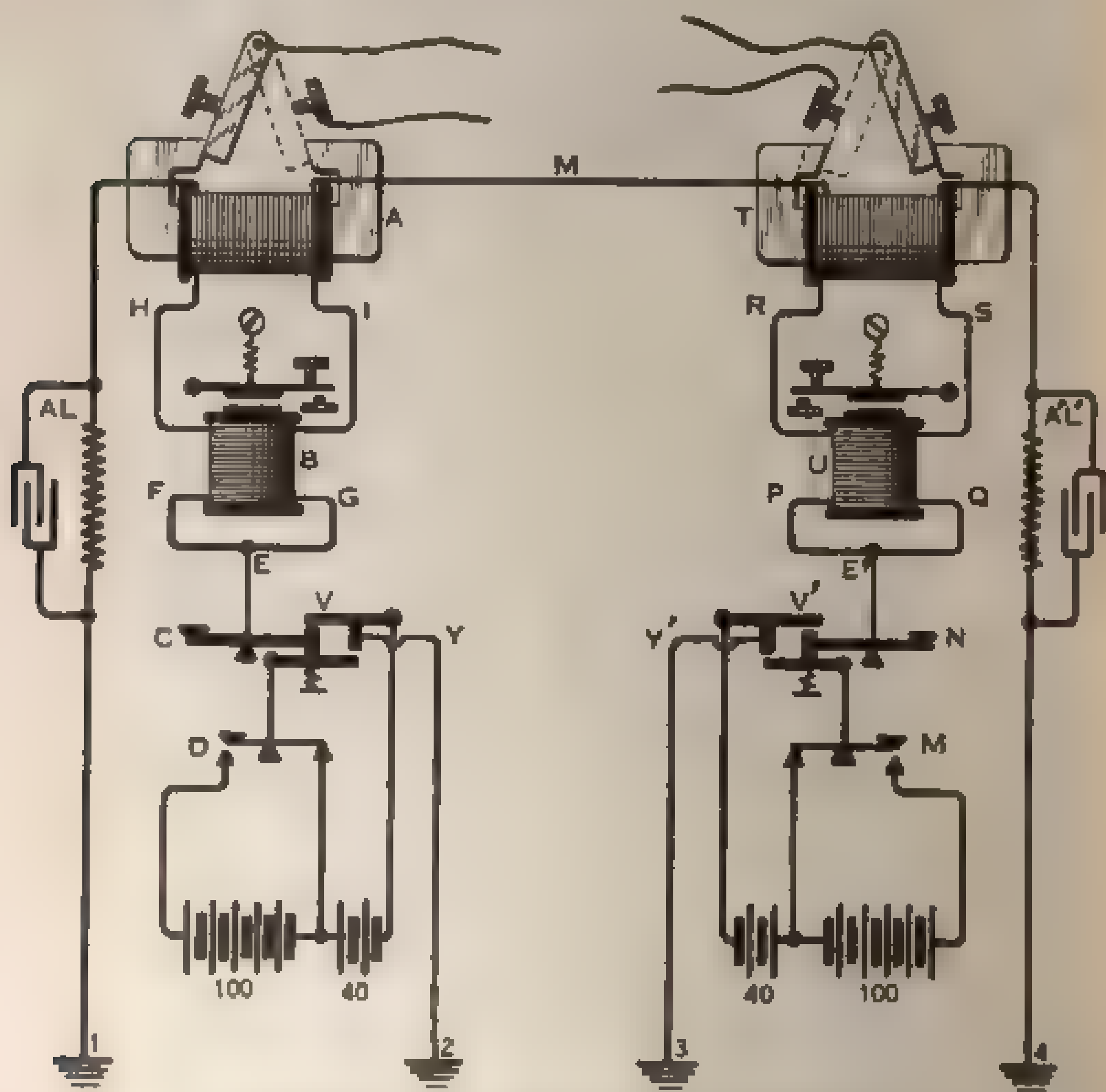

FIG 1224 —The quadruplex telegraph system

receiving operators at each end, or eight operators in all to handle the line. The equipment consists of a differentially wound polarized relay, *A*, Fig 1224, a differentially wound neutral relay, *B*, a pole changing key *C*, and a key governing the strength of the current, *D*, a 40-volt battery, and a 100-

volt battery at each end of the line. The artificial lines are balanced with resistance and capacity to correspond to the resistance and capacity in the main line. The pole-changing keys when depressed take the alternate position shown theoretically in Fig. 1222. The battery key merely governs the strength of current.

With no keys depressed, currents from the 40-volt batteries rise at each station to the dividing point *E-E'*. They cannot pass to the main line because the two voltages are equal and opposite. The current at one station, therefore, passes via *F* and *H*, through one winding of each of the two relays and thence via the artificial line *A-L* to the ground, 1, thence to 2, line *Y*,

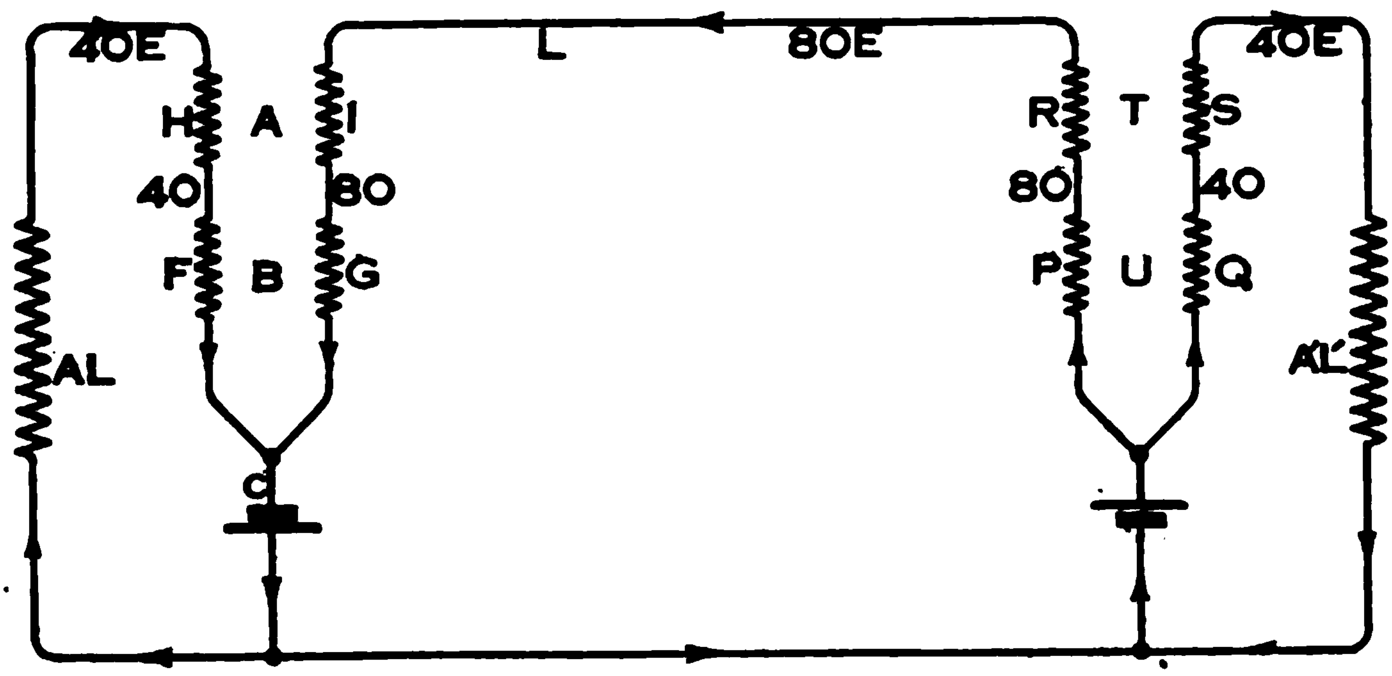

FIG. 1225.—Key C depressed.

contact *V*, and back to the battery. At the other station a similar current passes via *Q* and *S*, artificial line *A'-L'*, grounds 4–3, wire *Y'*, contact *V'* and back to the battery. These currents are not sufficiently strong to overcome the tension of the retractile springs on relays *B* and *U*. These relays therefore do not respond. The currents are in such a direction as to hold the armatures on the dead stops in relays *A* and *T*. Therefore these relays do not respond.

Next, if key *C* is depressed it takes the position shown in Fig. 1222. The actual connections now established are shown in Fig. 1225. The reversal of the 40-volt battery by the key *C* causes the current to flow into the winding *H* of the relay *A* in such a direction as to actuate this relay, but this battery being thrown in series with the battery at the distant station produces a current in the main line, *L*, under a pressure of 80 volts and

this current coming down through I produces a tendency twice as strong on relay A, tending to hold that armature on the dead stop. Therefore this relay does **not** close. The currents pass through the two windings of relay B differentially, one under a strength of 40 volts, the other under a strength of 80 volts, giving a net effect equal to the difference, or proportional to one current under 40 volts. This is **not** sufficient to actuate this relay. Hence relays A and B do not respond. At the other station, current is flowing through windings P and R under a pressure of 80 volts, in such a direction as **to actuate** relay T. It is flowing through winding S in such a direction as **not to actuate** this relay. The closing tendency, however, is the stronger and relay T responds. The differential effect of the

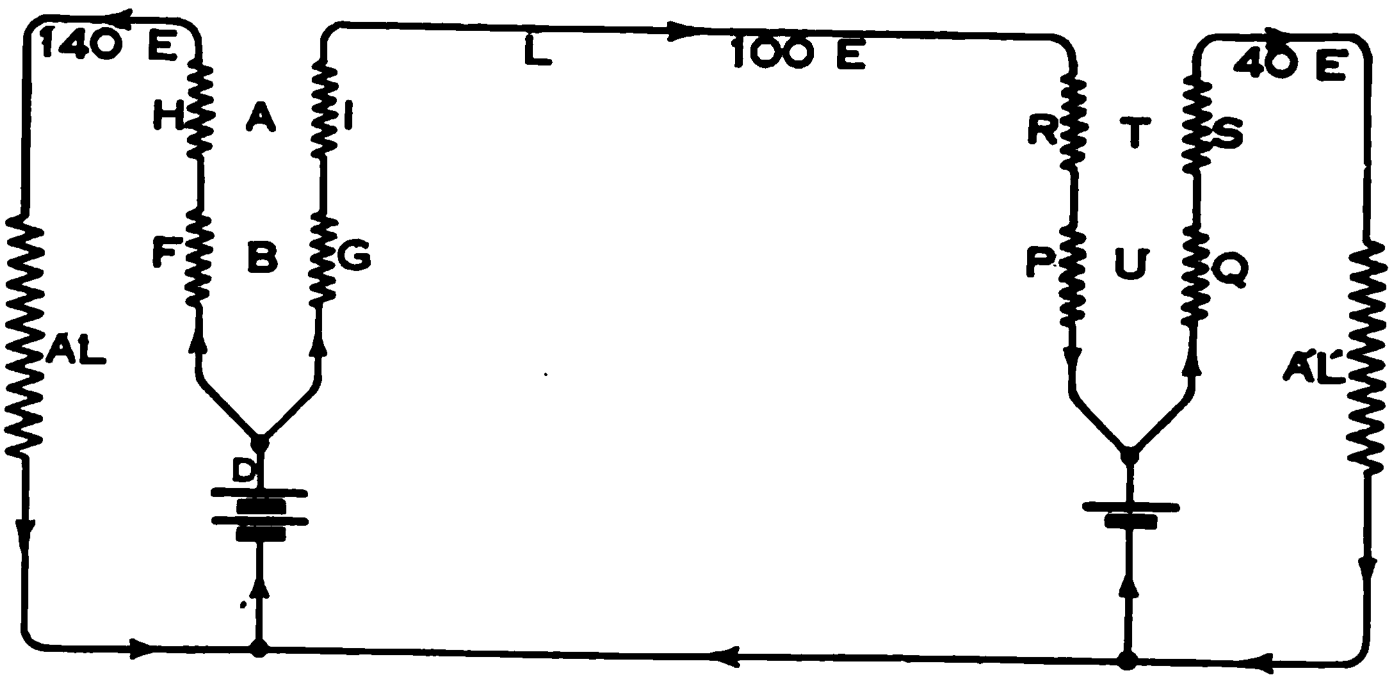

FIG. 1226.—Key D depressed.

currents in sections P and Q leaves a net effect proportional to 40 volts only and this relay, U, therefore does not respond. The current through the artificial line A'-L' returns to the battery at that station, while the current under 80 volts passes through P and R and returns via the main line L.

The next step will be to consider the effect when key D is closed. This is shown in Fig. 1226. Current under a pressure of 140 volts now rises through D and divides differentially through relays B and A. The current flowing through F and H is under a pressure of 140 volts. That to the right is under a pressure of 100 volts due to the opposition of the 40-volt battery at the distant station. The differential effect upon relays A and B is due to a current under a net pressure of 40 volts and is the same as when D was not closed. Therefore relays A and B

do not respond. The current flowing to the left passes through the artificial line and returns to the battery. Current flowing to the right passes through the main line *L* and down through *R* and *P*. Here it encounters the opposing e.m.f. of the battery at that station of 40 volts so that the net current in the main line is due to 100 volts. Current from the battery at the distant station rises through *Q* and *S* under a pressure of 40 volts and returns through the artificial line to the battery. As the current is flowing through *R* and *S*, in such a direction as to produce an added effect, the armature of *T* is held on the dead stop more firmly than before. As this current passes through *P* and *Q* in such a direction as to produce an added effect, the equivalent

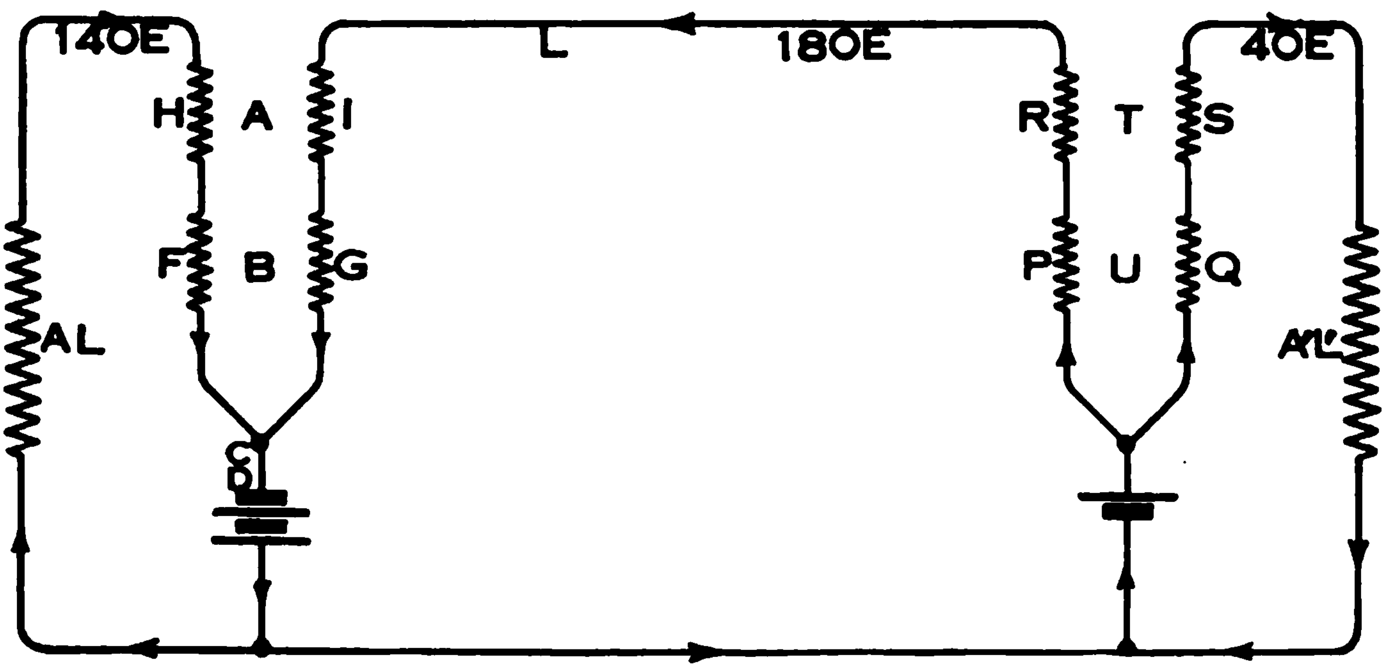

FIG. 1227.—Keys C and D depressed.

is as though 140 volts were applied to one winding and this relay therefore responds.

Next consider the effect of depressing both keys *C* and *D*. This reverses the polarity of the battery and directs the full pressure of 140 volts to ground as in Fig. 1227. Part of this current returns through the artificial line *A*-*L* under a pressure of 140 volts and comes back through *H* and *F*. The other portion passes through the ground and through the 40-volt battery at the other end, thence through windings *P* and *R* and returns through main line *L*, under a pressure of 180 volts. The currents through *I* and *G* are under 180 volts acting differentially with the current through *H* and *F* under a pressure of 140 volts. The action is differential and *A* and *B* do not respond. At the distant station, current passes through *Q* and *S* under a pressure of 40

volts from the battery at that station. The current passing through *P* and *R*, however, is differential with respect to the preceding current and is under a pressure of 180 volts. This gives a net excess of current due to 140 volts. This is of sufficient strength to actuate relay *U*, and in the proper direction to actuate relay *T*. These two relays thus respond.

The effect of depressing a pole-changing key *C*, at one station and a key giving high battery pressure, *M*, at the other station, will next be considered, Fig. 1228. Here, current from *C* is directed to the ground and returns under a pressure of 40 volts through the artificial line at that station and windings *H* and *F*. The current also divides and passes through the ground to the distant station and up through the 140-volt battery controlled

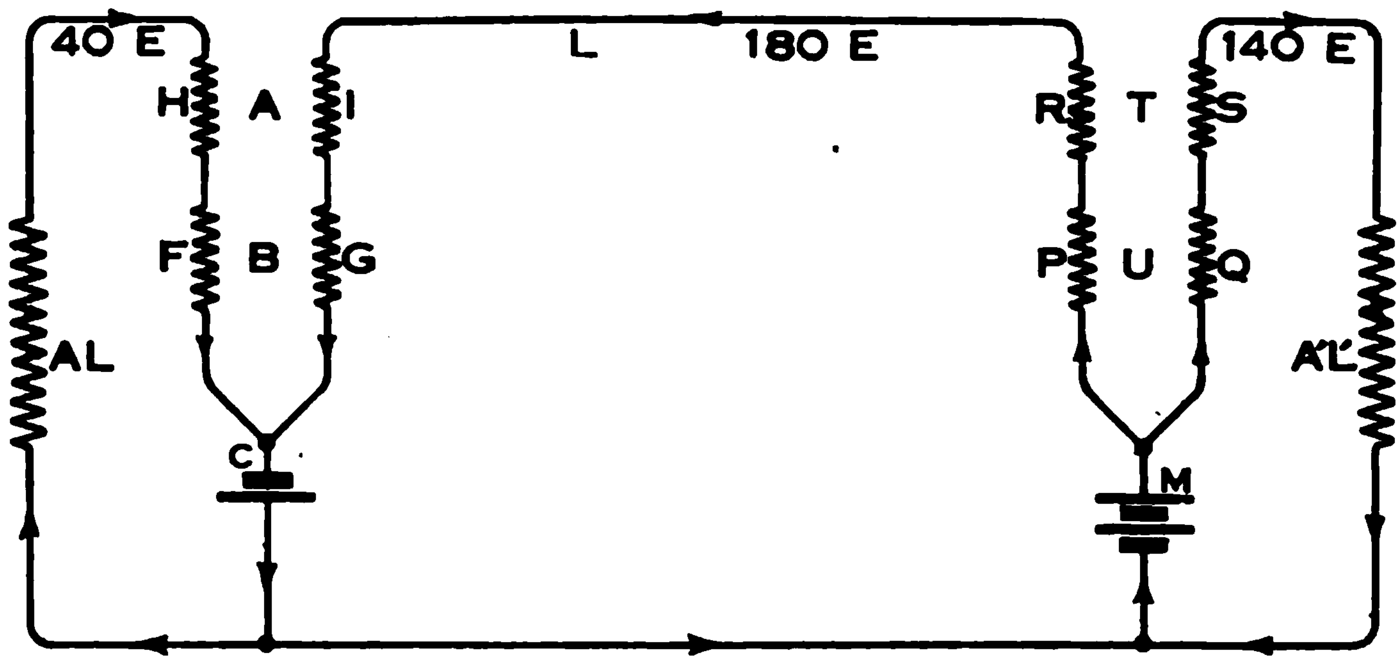

FIG. 1228.—Keys C and M depressed.

by key *M*. Here this current divides, that going through *P* and *R* being due to 180 volts as it is aided by the battery at the first station, while that passing through *Q* and *S* is under a pressure of 140 volts. The action on relay *T* is a differential one with an excess of 40 volts in a direction such as to close the relay. The action upon relay *U* is differential with an excess of 40 volts which is **not** sufficient to operate the relay. The current returning through the line passes down through *I* and *G* under a pressure of 180 volts. Here, the direction of current in *H* under a pressure of 40 volts is differential with respect to *I* under a pressure of 180 volts. The excess is 140 volts in such a direction as to hold the relay open. Relay *A* therefore does not respond. The current through *G* is under 180 volts while that through *F*, differential with respect thereto, is under

40 volts. The excess is sufficient to affect the relay and B therefore closes.

The next step to consider will be when keys C and D at one station and M at the other station are closed, Fig. 1229. This throws 140 volts to ground at the first station and 140 volts to line at the distant station. The artificial line A-L carries current under 140 volts, and the artificial line A'-L' also carries current under a pressure of 140 volts but in the opposite direction, while the main line carries current under 280 volts. The 280-volt current and the 140-volt current in the windings H and I are differential but with an excess of 140 volts in such a direction as to hold the relay A on the dead stop. The differential effect in F and G is with an excess in favor of G to the extent of

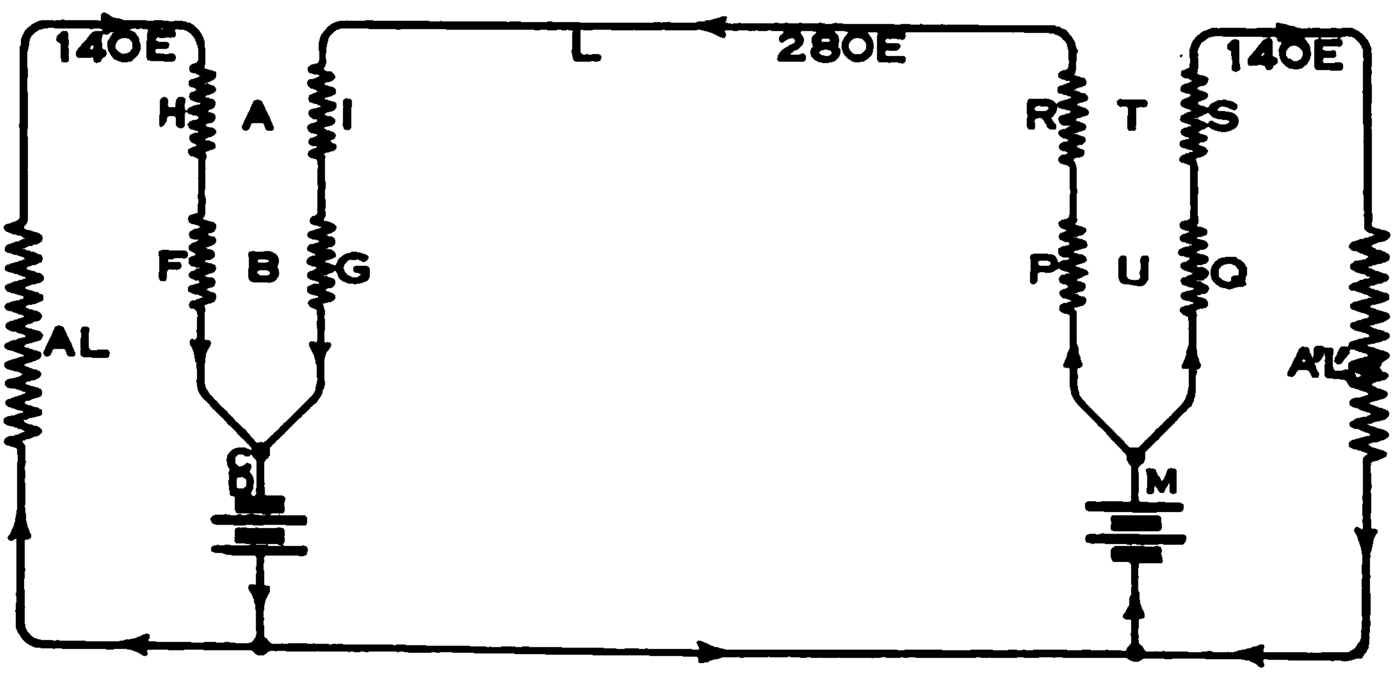

FIG. 1229.—Keys C, D and M depressed.

140 volts, and B therefore closes. At the distant station the current in P and Q is differential with an excess of 140 volts which is sufficient to operate U. The current in R and S is likewise differential but with an excess of 140 volts in R in a direction such as to close the relay.

The effect of closing keys C and D at one station and N at the other station is shown in Fig. 1230. The current in the artificial line A-L is under 140 volts and in A'-L' under 40 volts. The current may be considered as flowing through the ground and against the polarity of the battery at the distant station where it falls 40 volts in potential. This will give a current under an effective pressure of 100 volts, through P and R, returning through I and G, or this current may be considered as passing through the ground and up through the artificial line A'-L';

thence down through S and Q and back up through P and R, which gives the same effect as far as voltage in line L is concerned. This current is in such a **direction** in S and R as to affect the relay R and is of such a **strength** in Q and P as to operate relay U. In I the current under 100 volts is **not** in such a direction as to close the relay, but in H it is under a pressure of 140 volts, in such a direction as to **close** the relay. It therefore closes. Currents in F and G are differential with an excess of 40 volts in F which is not sufficient to operate it. The relay B therefore does not close.

Another condition which could exist would be when keys C and N were depressed. This would simply reverse the currents in the polarized relays and therefore operate both A and T.

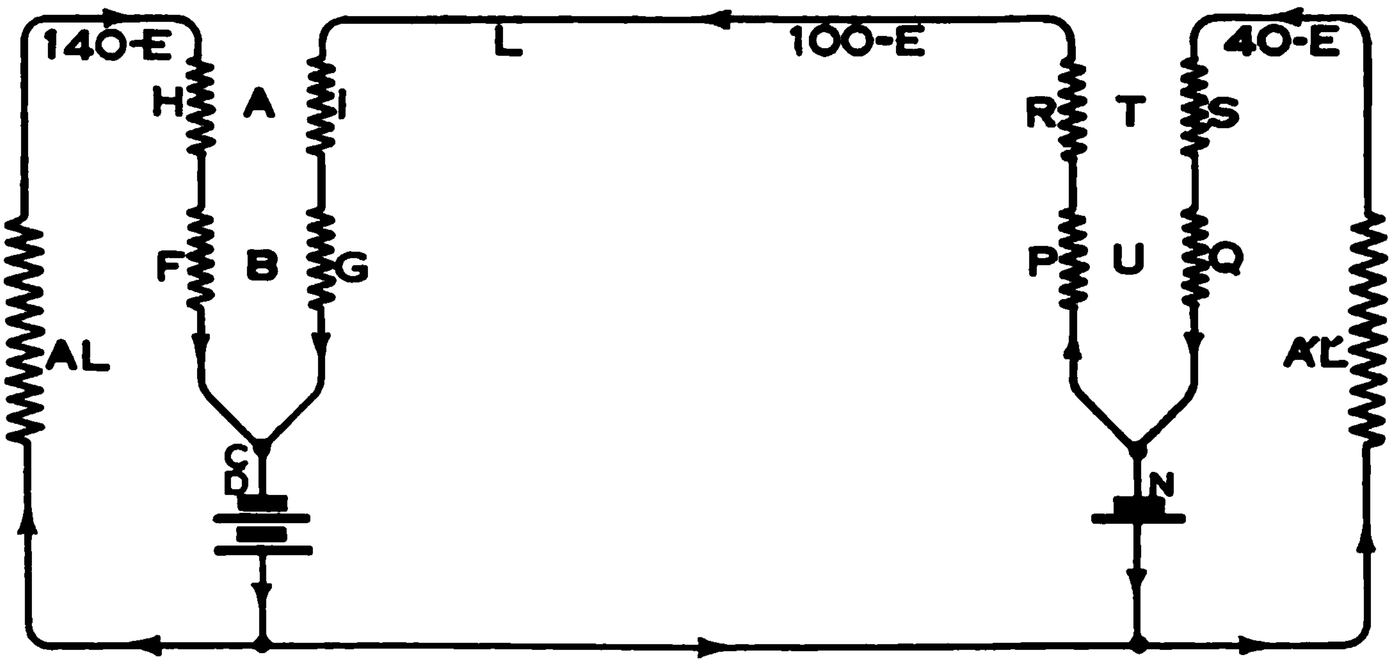

FIG. 1230.—Keys C, D and N depressed.

The depressing of keys D and M would increase the strength of the currents through F and Q and the artificial lines, and would therefore operate relays B and U, and the depressing of all four keys C and N, and D and M, would reverse the currents in all four relays, and make these currents of a maximum strength and therefore operate all four relays.

Thus when no keys are depressed or when keys C and N are depressed, or when keys D and M are depressed, or when all four keys are depressed, under all these conditions there is **no current flowing through the main line** L, although in every instance save when all four keys are open, signals are being transmitted.

The pole-changing keys and the polarized relays constitute the **polar** or the **No. 1** side of the quadruplex system. The neutral relays and the keys governing the strength of the battery

constitute the **neutral** or the **No. 2** side of the system. The actual device which is employed to transmit messages is called a transmitter.

Single telegraph lines cannot be operated successfully for more than from three to six hundred miles. The greater the 'ength of the line the greater will be the difficulties encountered through leakage and retardation due to self-induction until the rate of signaling is greatly reduced.

Repeaters

When it becomes necessary to operate lines of great length, the principle of the relay is extended from repeating into a local

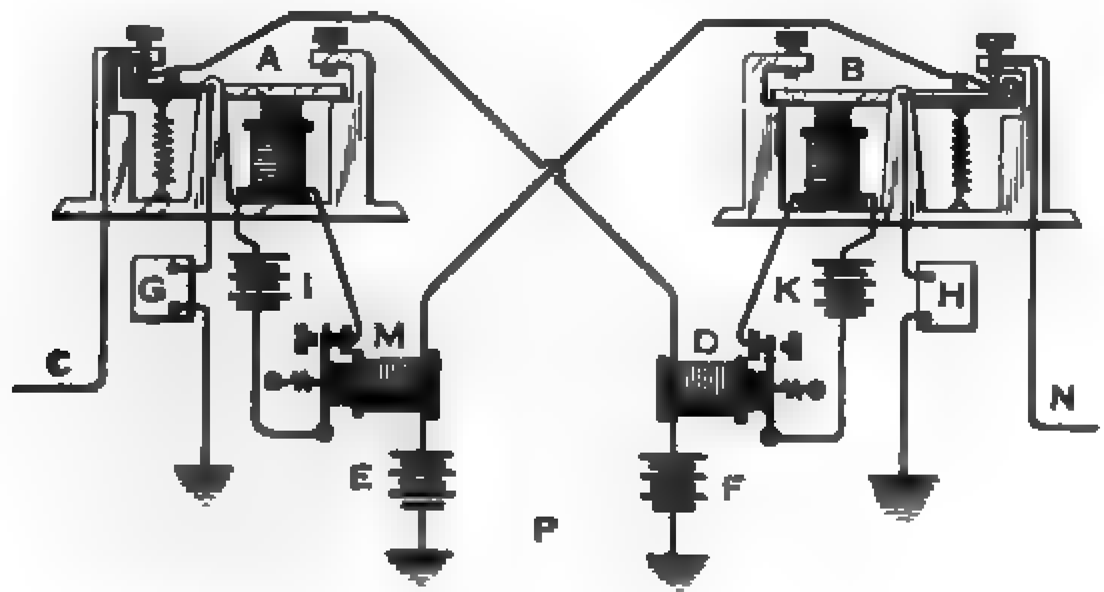

FIG. 1231.—Principle of the "Toye" repeater.

circuit, to repeating into another section of main line which is really a prolongation of the original circuit. One of the simplest devices of this sort is the Toye repeater shown in Fig 1231. Here, two transmitters, *A* and *B*, and two relays, *M* and *D*, are employed. There are sections of two main line batteries *E* and *F*, also limiting resistances *G* and *H*. Assume this to be a repeating station *P*, located at Pittsburgh, to relay messages from *N*, New York, to *C*, Chicago, the object of the circuits being to provide means by which New York can open and close the Chicago line, while at the same time Chicago can open or close the New York line. Current from the battery *F* flows normally through relay *D*, the spring and the upper screw of transmitter *A*, and out into the Chicago line, *C*, passing through the relay

at the distant point and back through the ground to *F*. Current likewise from *E* passes through relay *M*, flexible contact and upper screw of transmitter *B* thence to the New York line *N*, through the relay there, and thence back through the ground to *E*. These currents hold the relays *M* and *D* closed and the transmitters are likewise closed through the local batteries *I* and *K*.

If, now, New York breaks at the sending key, the circuit through *M* and *E* is interrupted and the relay armature released. This breaks the circuit on the battery *I*, and the transmitter *A*, releases its armature. This first causes the flexible tongue to be grounded through the hook and artificial line *G*, thereby holding the circuit closed on the battery *F*, which operates the Chicago line. This is necessary, otherwise the relay *D* would release, the battery *K* would be opened, the transmitter *B* would release, and the New York line would be opened on the upper screw contact of *B* and New York could not again regain control of the line. As the lever in transmitter *A* continues to descend, the tongue, under the tension of the spring, after closing on the hook, finally breaks from the upper screw and the Chicago Line is opened. Thus New York can open and also close the Chicago line at will. Chicago can likewise open and close the New York line, for the connections are in duplicate on each side of the transmitter.

This transmitter is also employed in some of the preceding systems as a key for changing the strength of the battery. When the transmitter is on open circuit the tongue and hook form a closed back stop. When the transmitter is energized the tongue first makes contact on the point of the screw, which is equivalent to closing the front stop, and thereafter breaks from the hook which is equivalent to opening the back stop.

Submarine Telegraphy

For submarine telegraphy, the Thomson mirror galvanometer was first employed. This was followed by the siphon recorder, which was a special arrangement of the D'Arsonval galvanometer, with a needle for tracing ink lines upon a moving tape and thereby recording the signals. A simple circuit for submarine telegraphy is shown in Fig. 1232. Double contact keys are employed and a battery at each end of the line. The re-

ceiving mechanism is located at *T* and *U*. A switch having two positions is located at each station. It is normally in the receiving position *R*, at station *B*. In order to send, the switch is thrown into the alternate position *S*, shown at station *A*. Depressing one of the two keys at *A* sends a current one way through the cable and back through the ground or sheath. Pressing the other key sends a reverse impulse through the distant receiver, causing it to deflect in the reverse direction.

For many years it was necessary to receive by sight, the signals consisting of a moving spot of light reflected from the mirror of a Thomson galvanometer on a screen. This required two men, one to read the signals and another to write them down. Later an irregular line traced on a tape by the siphon recorder left a permanent record which could be read by one man. Both

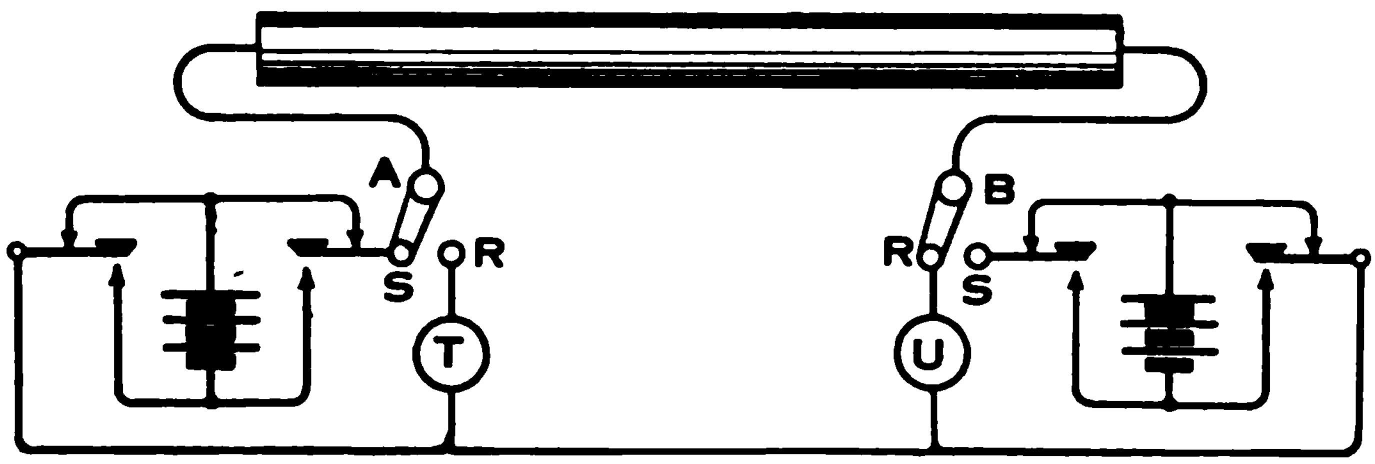

FIG. 1232.—Principle of submarine telegraphy.

methods required a manual operator to repeat the messages into the land lines. In later years, a system of delicate relays has been devised by which the impulses may be relayed without the medium of an operator into the local circuits from which they may be transmitted across the continent.

All important long cables are duplexed but no satisfactory method has been devised for quadruplexing long ocean cables.

Many systems of multiplex and high-speed telegraphy have been devised. The object in each case is to work the transmitting lines to their maximum capacity. The longer the line, the greater the difficulty. The speed of operation varies inversely as the square of the length, thus if a 300-mile cable could be worked by means of an automatic high speed transmitting apparatus at the rate of 320 words per minute, a 600-mile cable could be worked at the rate of 80 words per minute and a 1,200-mile cable at only 20 words per minute.

SECTION XXIII CHAPTER III

TELEGRAPHY

QUADRUPLEX SYSTEMS

1. Explain the principle of operation of the "quadruplex" system. State in detail the apparatus required.
2. Explain the object of the automatic repeater.
3. Explain the general plan of submarine telegraphy.

TELEGRAPHY

RADIO TELEGRAPHY AND TELEPHONY

Light, heat, magnetism and wireless telegraph waves are all forms of radiant energy, that is, they consist of ether waves propagated with the velocity of light, at about 189,000 miles per second, which is about 1,000,000,000 feet per second, and differ only in their length. The waves of ordinary sun light are about $\frac{1}{50000}$ of an inch long. Commercial radio systems employ waves which are identical in character but are about 1,250,000 times as long or usually about 600 meters.

The length of a wave is equal to the velocity of propagation divided by the frequency. Thus $\frac{V}{F}$ = wave length. With a frequency of vibration of 1,000 cycles, an ether wave then has a length of

$$\frac{1{,}000{,}000{,}000}{1{,}000} = 1{,}000{,}000 \text{ feet.}$$

When a commercial alternating current passes back and forth through a transmission line at the usual frequency of 60 cycles, the length of the wave set up in the ether is;

$$\frac{1{,}000{,}000{,}000}{60} = 17{,}000{,}000 \text{ feet or about } 3{,}000 \text{ miles.}$$

Light waves are **free,** that is, they radiate in every direction. The waves employed in radio transmission are **bound,** that is they glide over the surface of the earth as water waves over the surface of a body of water. In a light beam there are found, luminous, thermal and actinic rays. These also are distinguished from each other by their length. The luminous rays pass through glass but do not pass through hard rubber. The thermal rays will pass through hard rubber but will not readily pass through a vessel of water saturated with alum. The actinic rays which affect the photographic plate will pass readily through ordinary glass but will not pass through red glass.

The waves employed in radio transmission depend for their effectiveness upon their length. Short waves are readily absorbed by sun light. Long waves are not absorbed by sun light. Short waves become clogged in city buildings. Long waves are not so clogged but pass with the greatest freedom through cities. Short waves permit of transmission but a short distance over land or water. With long waves transmission can be carried on over great distances.

If a flexible wooden strip such as a yard stick, be rigidly held at one end so that the other is free to vibrate, and it is then set in vibration, the length of the waves set up in the air will be four times the length of the rod.

Every electrical circuit, likewise, has a definite natural frequency at which electrical charges, once started, tend to oscillate therein.

If an electrical charge is set oscillating in an aerial wire, such as is used for radio telegraphy, this charge will tend to oscillate naturally at such a rate as to send out electro-magnetic waves in the ether, four times the length of the aerial.

The frequency of alternation employed in radio currents is very high, ranging from 10,000 to 300,000,000 cycles per second. This causes these circuits to act very differently from those employing the ordinary frequency of 25 to 60 cycles, used in power work. A very few turns of wire will, therefore, produce a formidable inductance in radio work and condensers of such small capacity as to prevent the flow of low-frequency power currents readily pass radio currents. Furthermore, mutual inductance of one circuit on another is much greater with radio frequencies. With high frequency currents the impedance of a circuit depends almost entirely upon the reactance, and very little on resistance. By properly adjusting the frequency in a circuit the impedance may be made practically zero. This is because the inductive reactance increases with the frequency, while the capacity reactance diminishes. At some definite frequency, then, the magnetic reactance of a coil must have the same value as the capacity reactance of a condenser in series therewith, and since their e.m.fs. are in opposition the total impedance will be zero. When this condition occurs the particular frequency required is called the "resonance frequency" of the circuit, and the circuit is said to be "in resonance," or to be "tuned" to the frequency in question. As pointed out in Section XIV, Chapter VI, the condition for

resonance is when $6.28\,nL = \frac{1}{6.28\,nC,}$ from which the frequency of resonance must be $n = \frac{1}{6.28\sqrt{L\,C.}}$ If therefore a coil possessing an inductance of 0.0005 henry is placed in series with a condenser having a capacity of $\frac{5}{10^9}$ farad, the resonance frequency will be found to be about 100,700 cycles per second.

Magnetic Field

Every alternating current has associated with it a magnetic field which may be considered to be the sum of two components having entirely different characteristics, one called the **induction field** and the other called the **radiation field.** At the commercial frequency of 60 cycles, used in power work, the induction field is the only one of importance. It is this field which is employed in the ordinary transformer. It is the same field which is the basis of cross talk between parallel telephone circuits. When an ordinary type of antenna employed in radio work is energized with an alternating current it is found that the induction field produced is inversely proportional to the square of the distance from the antenna. **The induction field is not important in the usual applications of radio communication.**

The radiation field is transmitted by wave motion. The intensity of the radiation field varies inversely as the simple distance from the source, instead of varying inversely as the square, or, in some instances, as the cube of the same distance. The induction field produced by a current in a coil at a distance of 10 miles from the coil is only $\frac{1}{1000}$ of the strength of the induction field at a distance of 1 mile. The radiation field due to a current in a coil at a distance of 10 miles from the coil is $\frac{1}{10}$ of the strength of the radiation field at a distance of 1 mile from the coil. For communication over any considerable distance it is therefore necessary to make use of the radiation field. The **strength of the radiation field** is **directly proportional** to the **frequency** with the ordinary type of antenna. If a coil type of antenna is used, the strength of the radiation field is proportional to the square of the frequency. Successful communication can therefore only be obtained by employing high frequency.

An ordinary elevated antenna acts primarily as a condenser, while a coil antenna acts primarily as an inductance. In both types of antennas an approaching radio wave induces an e.m.f. in a wire or arrangement of wires.

Oscillator

The simplest possible form of wave transmitter is a straight wire cut in two by a small spark gap. The gap becomes conducting when a spark passes, so that the entire circuit between the aerial and ground is continuous, and in this circuit the currents oscillate, thereby producing the radiating waves in the ether. Fig. 1233 represents the simplest form of oscillating circuit for telegraph signaling. *B* is a battery or other source of direct current which energizes the primary of an ordinary induction coil *C*. The discharge from the secondary of this coil across the spark gap *G*, energizes the aerial, *A*, and causes oscillations to surge between the upper terminal and the earth. The inductance of this circuit may be varied by shifting the point of contact on the tuning coil, *E*. The signals are controlled by key *K*. For large stations an alternating-current generator, *A*, Fig. 1234, replaces the battery. A transformer, *T*, raises the pressure to 10,000 or 20,000 volts. This causes a discharge across the spark gap, *G*, which produces a series of oscillations in the circuit *G-K-P*. *P* is the primary and *S* the secondary of a type of transformer especially adapted for high frequencies and provided with an air core, and the impulses from *P* are handed through inductively to *S* and the circuit containing the antenna *D*. The frequency of supply containing the key, *F*, is low, as in the preceding form of transmitter. Whenever a spark passes across a gap, in a circuit possessing inductance and capacity, however, high frequency oscillations are induced. These oscillations constitute the source of the **radio frequency** employed in radio transmission.

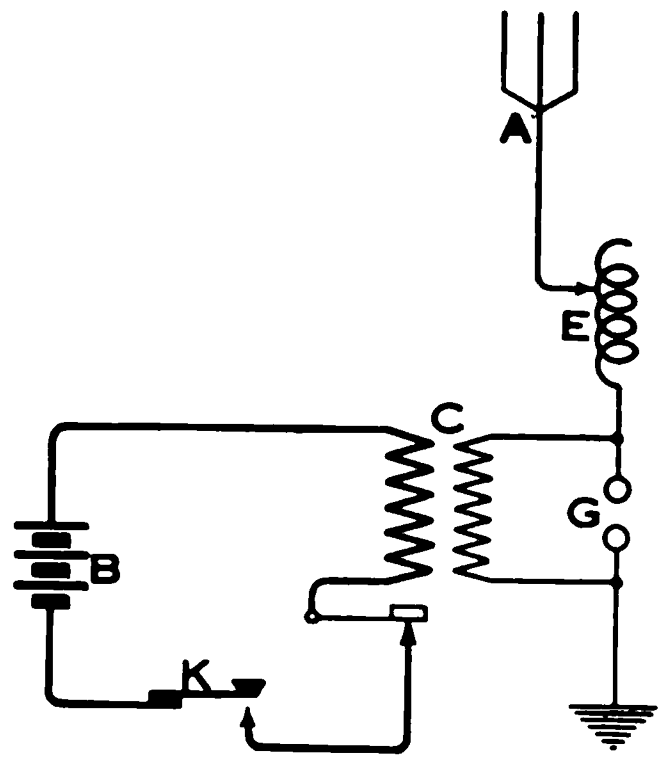

Fig. 1233.—Simple oscillator employing induction coil and battery for sending wireless telegraph signals.

A still better plan is to employ a specially designed high frequency alternator which energizes the aerial directly.

High frequency alternators containing upwards of 600 poles and running 10,000 revolutions per minute have been devised by Alexanderson. These machines produce currents with a frequency of 100,000 cycles per second.

Where the aerial line is directly connected to the source of supply, it is said to be **directly coupled,** Fig. 1233. When the aerial is separated electrically from the source of supply but is connected through the relation of the primary and secondary of

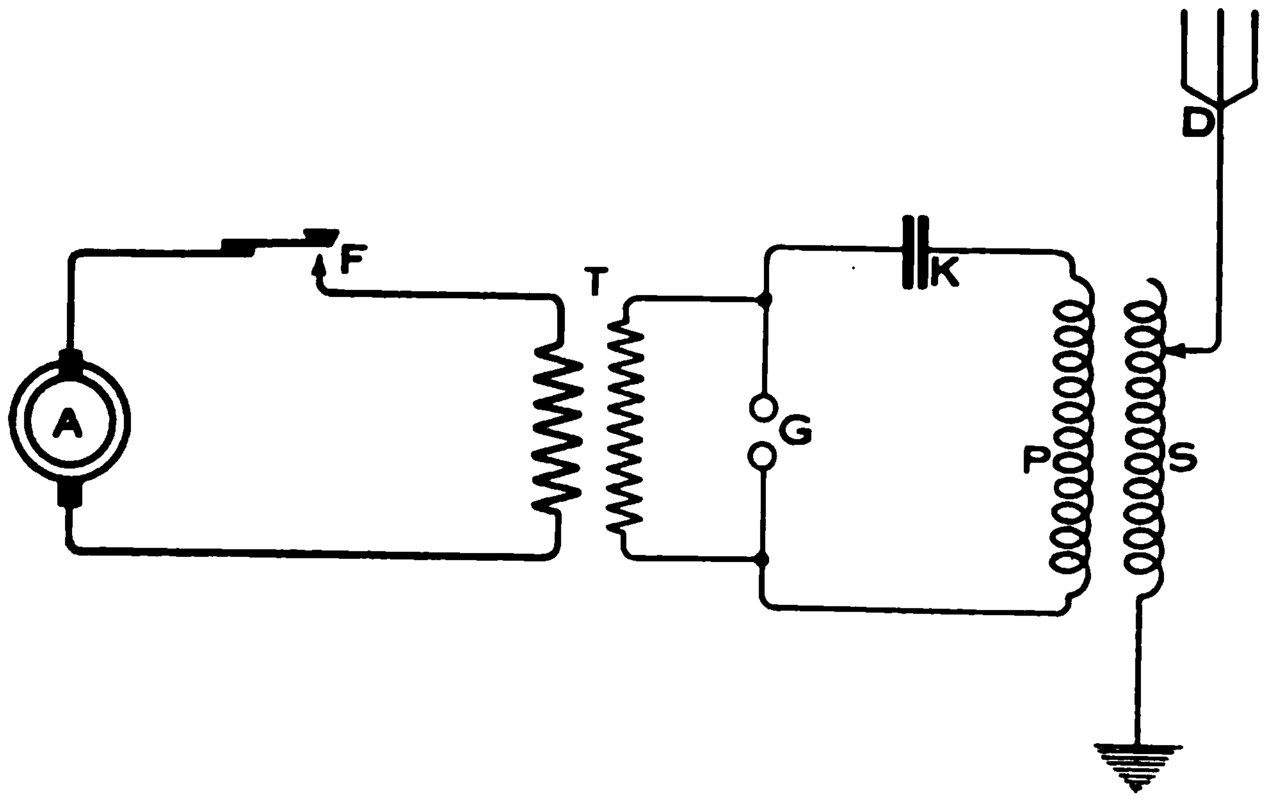

FIG. 1234.—Oscillator employing alternator and step-up transformer with inductive coupling to antenna circuit, employed for wireless telegraph transmission.

an induction coil with an air core, it is said to be **inductively coupled,** Fig. 1234. Depending upon the relative position of these two coils it is said to be **close coupled or loose coupled.**

Rotary Gap.—If the source is inductively coupled to the aerial, the current in the secondary and the aerial circuit reacts upon the primary oscillating circuits and damps out the primary oscillations. In order that a large amount of energy shall be radiated, it is necessary that the spark gap shall be rendered non-conducting after the first transfer of energy into the aerial circuit. To accomplish this, various devices have been constructed. One of the earliest was the synchronous rotary spark gap due to Marconi. When the spark was produced, a rotating segment was in line with a stationary segment, in order that energy might be transferred. Immediately after the transfer of the impulse, the rotary

segment moved away from the stationary segment, and lengthened the gap so that the return of energy from the aerial to the primary circuit was prevented.

Quenched Gap.—The quenched gap due to Von Lepel has also been successfully employed. This consists of two massive discs of copper separated about 1/100 of an inch, the gap between being sealed. Under a pressure of from 300 to 500 volts a current of 2 amperes is very readily passed, but the inductive return of energy through the gap is checked.

A quenched gap due to Penkert consists of two rotating discs revolving in opposite directions, separated about 1/250 of an inch. A quenched gap employed by the Telefunken company consists of a series of discs separated 1/100 of an inch. It employs about 1,200 volts per gap. It is very efficient and insures the radiation of between 60 and 75% of the energy transmitted.

Tuning

The practical importance of resonance lies in the fact that it enables the impedance of a circuit to be made equal to the resistance alone. It must be remembered that the reactance of the small inductances in a circuit, which are unavoidable, becomes important at radio frequencies, and often may be much greater than the resistance. This fact, taken in connection with the smallness of the e.m.f. of the incoming signals, would make it impossible to obtain any more than very minute currents in the receiving apparatus with inductance alone in the circuit. From this standpoint the sole function of the tuning of a circuit to resonance is to offset the inductive reactance by an equal capacity reactance, so that the impedance may be made as small as the resistance.

A circuit may be tuned to resonance in three ways:

1. By adjusting the frequency of the applied e.m.f.
2. By varying the capacity of the circuit.
3. By varying the inductance of the circuit.

Waves

Fig. 1235 pictures the electrostatic field existing across the gap of a simple oscillator before the gap becomes conducting. When a spark passes and the gap becomes conducting the straight electric lines of force existing across the center of the gap vanish, and those from each side begin to move up under the unbalanced

sidewise pressure as before. When the ends of the first curved line reach the gap we must suppose that the momentum causes the ends to cross and the middle portion travels across the gap.

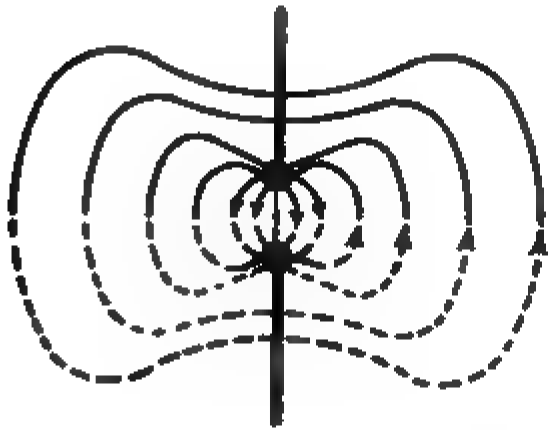

FIG. 1235.

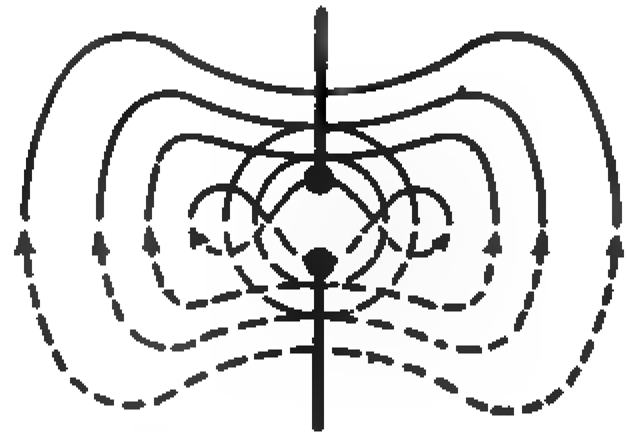

FIG. 1236.

This state of things is represented in Fig. 1236. The crossing of these lines will result in the formation of a loop, as shown, and as

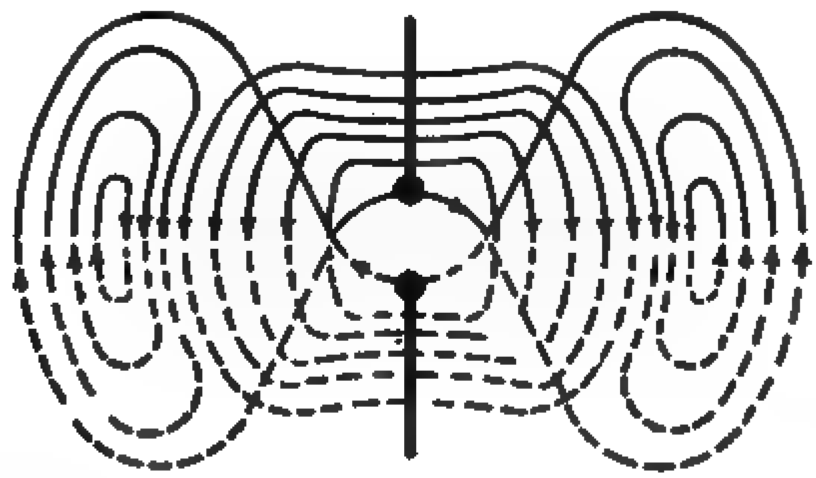

FIG. 1237.

this loop breaks into two parts the condition shown in Fig. 1237 results. The process goes on until one-half of an oscillation has

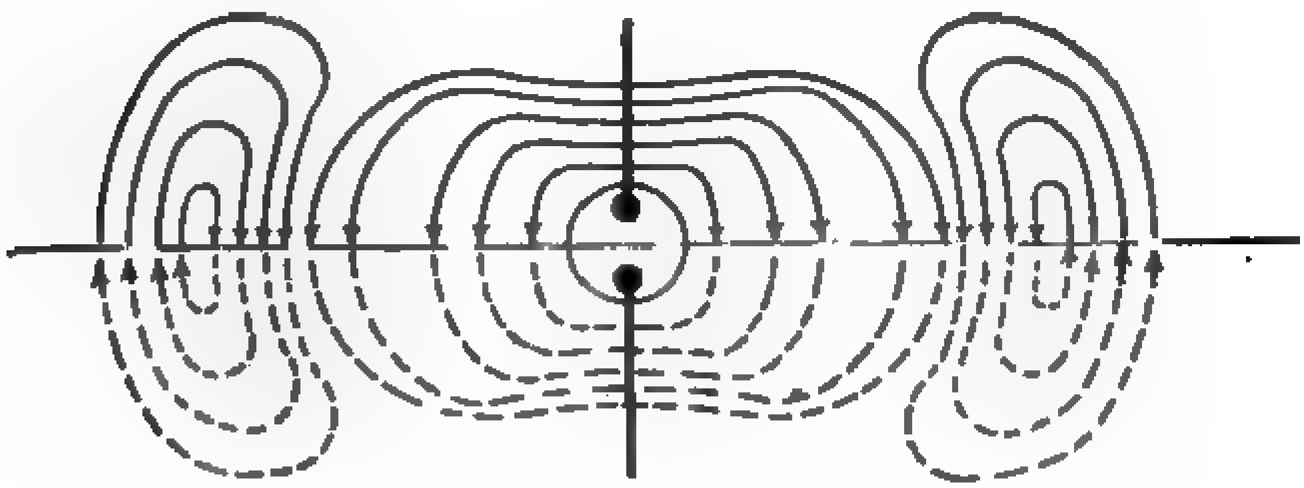

FIG. 1238.

been completed. The condition then existing is represented by Fig. 1238. Now, as the lower end of the oscillating circuit is

grounded, the portion of the waves below the horizontal line in Fig. 1238, does not appear and the upper portion glides out in ever-widening circles, a sectional view of which is shown in *A*, Fig. 1239. The form of the wave is shown at *B*, and the magnetic field is shown in plan at *C*.

When a stone is dropped into a quiet pool of water a train of waves is started, which radiate in all directions, leaving the surface behind undisturbed. If a second stone is dropped just at the moment when the surface at the starting point has completed one up-and-down excursion, another wave train will start in phase with the first and the two will form one train. If the process is repeated, once after each complete vibration of the surface at the starting point, continuous waves are produced. Continuous waves are produced by an organ pipe when the key is held down. Discontinuous or damped waves are produced by a piano when a key is struck. An ordinary induction coil producing a spark across the gap of an oscillating circuit, as in Fig. 1233, generates a series of dis-

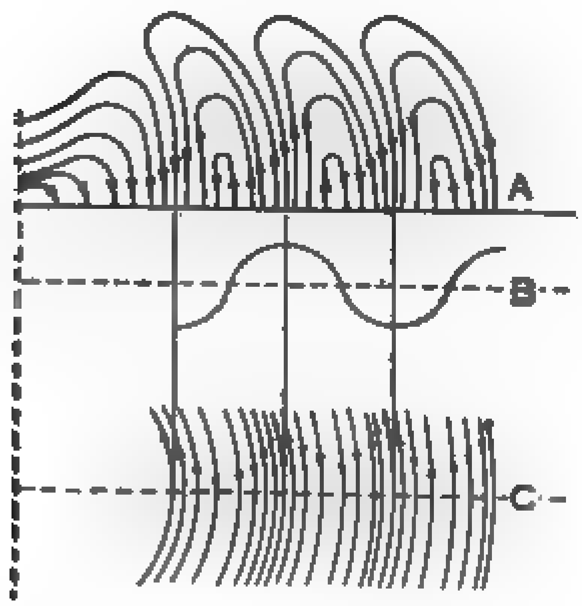

FIG. 1239.—(*A*) Electric field radiating from antenna; (*B*) Form of alternating-current wave in antenna; (*C*) Plan view of electromagnetic field radiating from antenna.

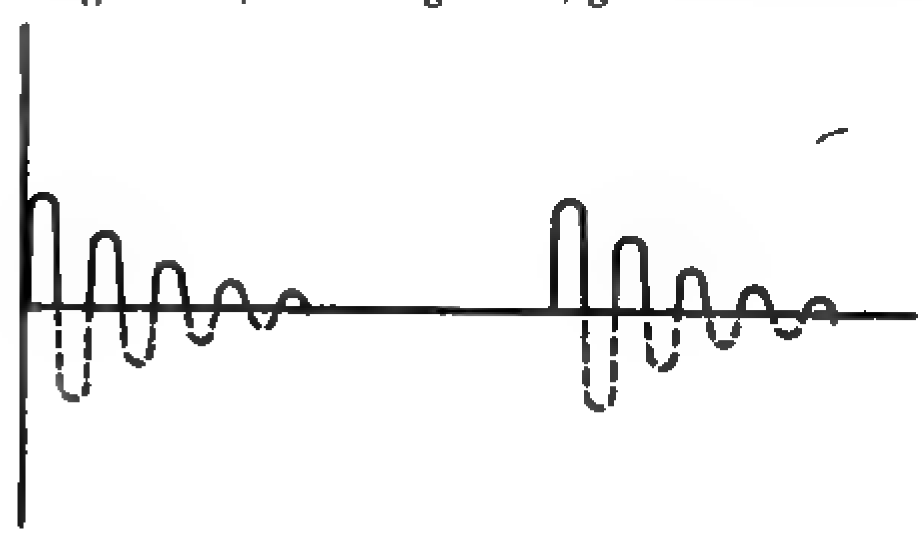

FIG. 1240.—"Damped" wave trains sent out by antenna with spark system of transmission.

continuous or damped wave trains, one train for each spark. This is illustrated in Fig. 1240. An electric arc, or an electron

tube employed as an oscillator, generates continuous or undamped waves, somewhat like Fig. 1241, but more exactly like Fig. 1253. With damped wave trains the oscillations die away, depending upon the resistance of the circuit and upon the in-

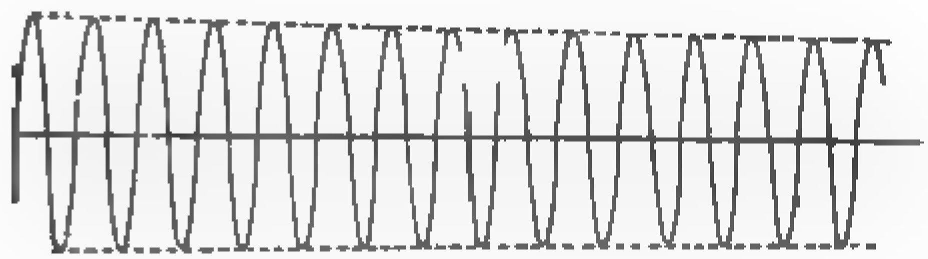

Fig. 1241.—Wave train, very slightly damped.

ductance encountered, as in Fig. 1242. The greater the resistance and the smaller the inductance the more rapid is the damping and the rate at which the oscillations decrease, as in Fig. 1243. Under fixed conditions it will be found that if the second maximum of a radio wave is 9/10 of the first, the third will be 9/10 of the second, and so on. This measure of the rate of decrease is called the

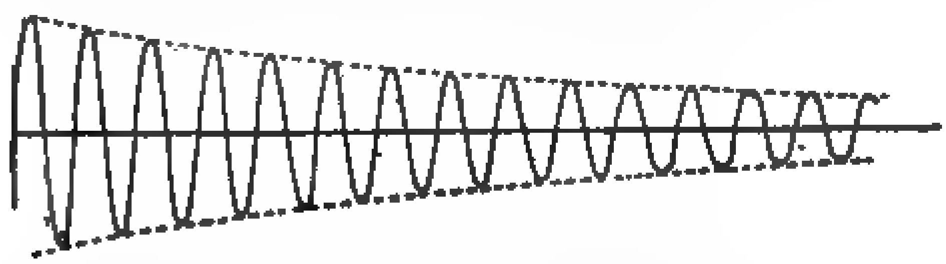

Fig. 1242.—Damped wave train.

decrement, and refers to the rate of decrease in the amplitude of the wave per complete oscillation. In the mathematical theory of damping it is more convenient to adopt the natural logarithm of the ratio of any maximum to the next following maximum. This number is known as the **logarithmic decrement.**

Antennas

A single vertical wire, Fig. 1244, forms an antenna which is entirely symmetrical for radio waves traveling horizontally, and such a wire has no directional effect. The directional characteristic of such an antenna may be represented by a circle drawn with the foot of the wire as a center.

The inverted "L" antenna with long, low top, Fig. 1245, widely used in large stations, has a marked directional effect. The directional characteristic of such an antenna is shown by the figure at the bottom of this sketch, in which the length of the

lines drawn from the central point indicates the strength of the current received from a transmitting station located in that direction. It will be noted that the inverted "L" transmits and receives best in the direction opposite to that in which the antenna top points. Fig. 1246 illustrates the general appearance of the widely used inverted "L" antenna.

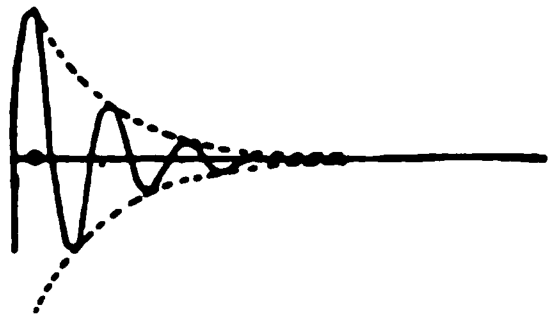

FIG. 1243.—Sharply damped wave train.

Aerials or antennas for receiving should be placed at least 35 feet above the ground, and clear of all buildings or towers if possible. A single wire 60 to 130 feet in length is sufficient for small stations. This should be well insulated from the supports and all trees or grounds. The "lead in" wire should clear all buildings and come as directly down to the receiver as possible. **All joints must be soldered.** The antenna must be equipped with a ground connection, and switch, external to the building by which it can be grounded when not in use, to provide protection against lightning. This ground may fasten to a water pipe if at hand. The receiving circuit itself also requires a good ground connection. The wire used in the aerial should be noncorrosive or insulated if possible and should be at least No. 18 B. & S. The ground leads should be No. 4 or No. 6.

Aerial masts may be of either wood or iron. They need not be insulated in sections or from the ground.

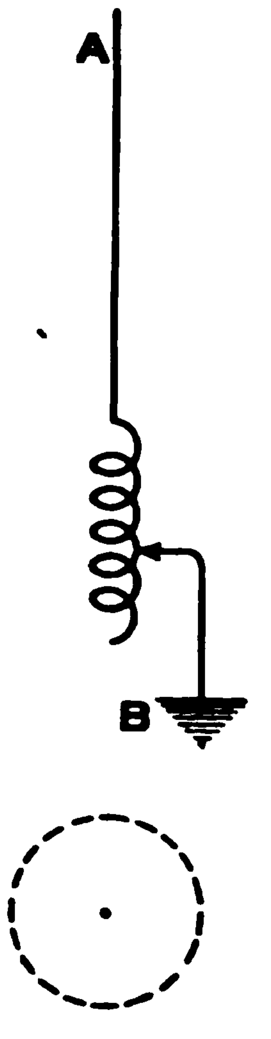

FIG. 1244.—Simplest form of vertical antenna.

Detectors

To detect the ether disturbances set up by the oscillator a receiving aerial is employed. This is a duplicate of the sending aerial; in fact, the same aerial circuit may be utilized for both sending and receiving.

The fundamental principle upon which radio signals are received is that of resonance. By varying either the inductance or the capacity, or both, of the receiving circuit, the circuit may be tuned so that currents, once started therein, will oscillate at the same natural frequency as that of the incoming waves. The result will be that the incoming waves, though extremely feeble, will, after a few alternations, build up comparatively large os-

cillations in the circuit. To receive radio signals, then, all that is necessary is an antenna circuit tuned to the same wave length as that of the receiving station, and an instrument capable of detecting the current which flows in the antenna circuit.

Coherer.—The first detector of ether waves was the coherer, originally discovered by Hughes in 1879, and rediscovered by

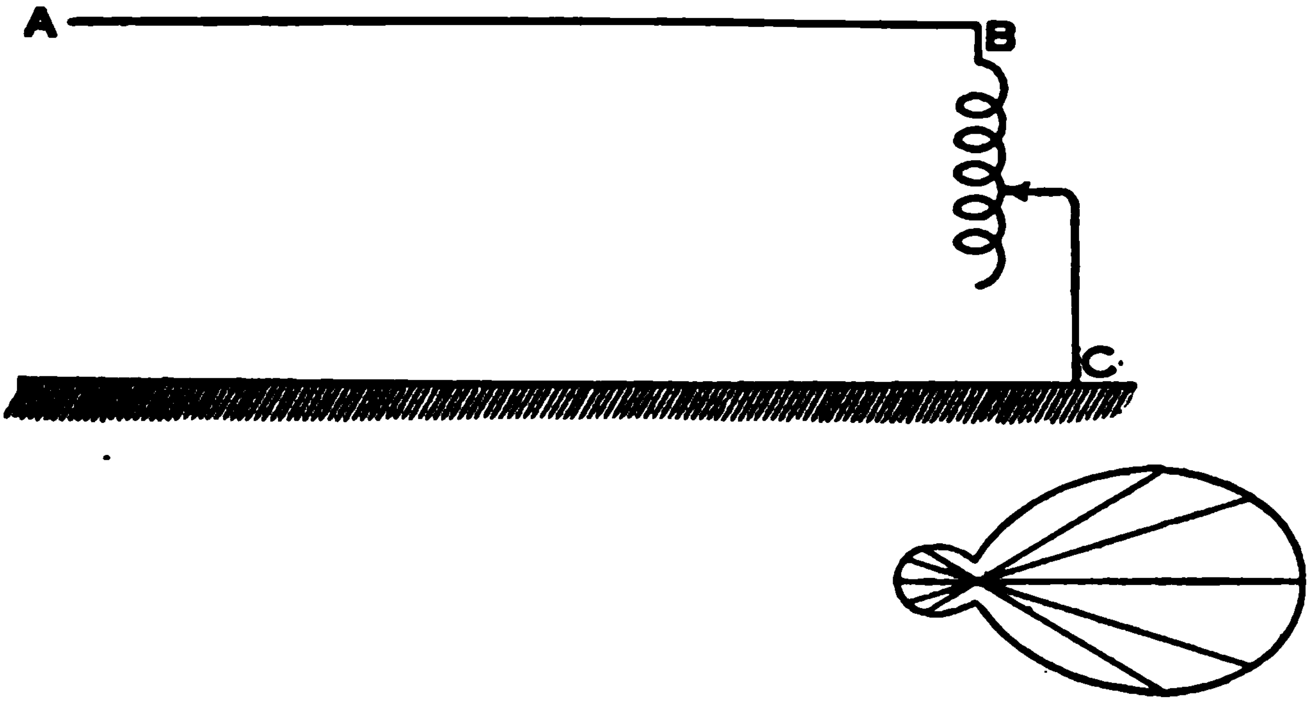

FIG. 1245.—Inverted "L" form of antenna showing directional force.

Branley in 1890. In its simplest form it consists of a glass tube about ¼ of an inch in diameter with two electrodes preferably

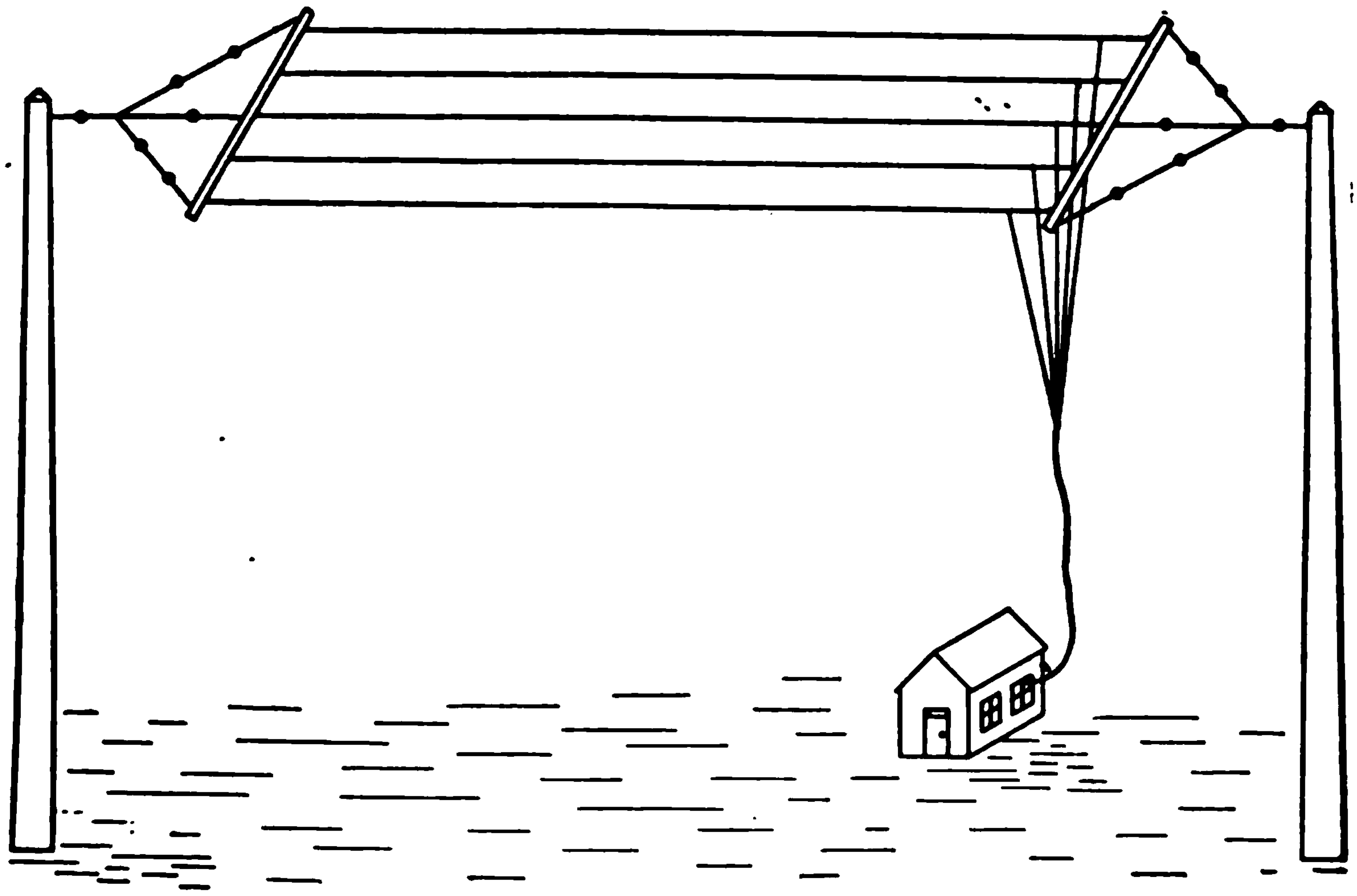

FIG. 1246.—General appearance of commercial form of inverted "L" antenna.

of nickel, separated one-fourth of an inch or more. The space between the electrodes is filled with fine iron or nickel filings. The resistance across these filings is normally several thousand

ohms. The filings bridge the gap in the receiving circuit corresponding to the position occupied by the spark in the transmitting circuit. Just as soon as ether waves strike the receiving aerial they set up oscillations therein. The receiving aerial then acts as a secondary of an induction coil, of which the sending aerial is the primary. As the charges induced in the secondary surge across the gap containing the iron filings they are caused to cohere. That is, they arrange themselves in metallic chains between the electrodes and the resistance falls. A battery and relay in series, are connected in shunt with the coherer. As soon as the resistance of the coherer drops, the relay is energized and the impulse is transferred into a local circuit where it may be made to actuate a telegraph sounder. Following this crude device, which was perfected in 1895, by Marconi, there were a number of coherers and other detectors designed. The microphone such as is used in telephony was also employed to a limited extent. These detectors were of two classes: First, those acting as triggers which were tripped by the ether wave, and the impulse thus relayed into a secondary circuit. Second, those acting as valves permitting the resistance of the circuit to drop when the electrical potential was raised to the proper value.

Detectors may be classed under three heads. The solid, due to Dunwoodie, which includes the carborundum and other crystal detectors. The liquid, known as the barretter, due to Fessenden, and the gaseous due to DeForest, which is generally known as the audion.

Crystal Detectors.—The properties of the crystal detector are quite remarkable. Due to the peculiar structure of carborundum, the resistance of such a crystal is widely different if measured with currents flowing through it in opposite directions. Three separate crystals gave the following results: With the first, the resistance measured one way was 102,000 ohms; the other way, 32,000 ohms. The second measured 22,000 ohms in one direction and 13,000 ohms in the other direction. The third, 1,000 ohms in one direction and 500 ohms in the other. Thus crystals manifest a rectifying property similar to the mercury arc and the aluminum cell, readily permitting current to flow in one direction but checking its flow in the reverse direction.

Silicon and perikon are also used for detectors. These crystals have the same resistance with the current in both directions, if

provided with heavy contacts. They also develop a rectifying property, which, however, is due to change in resistance at the surface contact.

From laboratory experiments the order of sensitiveness has been ascertained to be the following:

1. Iron Pyrites.
2. Galena.
3. Perikon.
4. Silicon.
5. Carborundum.

The last named seems to give the best results when employed with an e.m.f. of about 0.3 of a volt in series therewith. All crystal rectifiers seem to work better when assisted by a small external e.m.f.

The very simplest form of receiving circuit is shown in Fig. 1247. Here a detector, *D*, which may be a simple carborundum crystal, bridges the gap in the antenna circuit and is shunted by a pair of telephone receivers, *T*. Now the diaphragm of a telephone receiver cannot follow the very rapid radio frequency variations. Every time a spark passes the gap in a transmitting station a series of oscillations is produced, which project a wave train through the ether. A series of these wave trains, due to a succession of sparks, is illustrated in Fig. 1240. The high frequency does not succeed in moving the telephone diaphragm at all. To overcome this difficulty, the crystal detector *D*, Fig. 1247, is placed in the circuit, which permits the current to flow in one direction but not in the other. The high resistance of *D* in one direction forces one set of alternations through *T*. The low resistance of *D* in the other direction permits all of the reverse alternations to pass through *D*, being aided by the opposing self-induction of *T*. The cumulative effect of one wave train, therefore, is to cause the telephone diaphragm to be pulled in one direction, but prevents it from being affected by the reverse alternations, due to the valve-like action of the detector. The wave train produced by one spark produces the effect of a single pull on the telephone diaphragm, and when the transmitting key is depressed and a series of sparks are produced, the telephone receiver vibrates as many times as there are sparks per second. The frequency which is thus heard is called the **audio frequency,** and is equal to the number of complete wave trains per second.

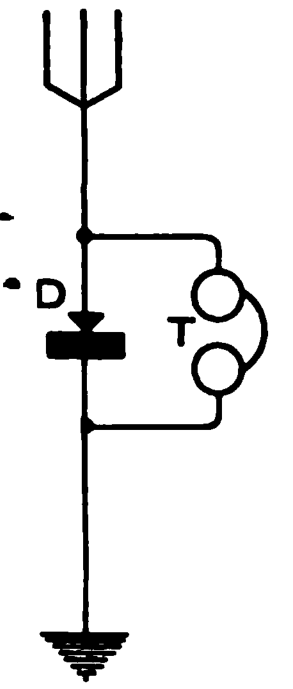

FIG. 1247.—Simplest form of receiving circuit with crystal detector.

The frequency of the alternating currents in the transmitting antenna, upon which the propagation of radio signals is based, is called the **radio frequency.** With a 300-meter wave, having 1,000 wave trains per second, the radio frequency is 1,000,000, and the **audio frequency** is 1,000; that is, one is one thousand times higher than the other. The human ear can only detect a maximum audio frequency of between 16,000 and 20,000 waves per second. Although the rectifying crystal, *D*, Fig. 1247, is commonly called a detector, it detects nothing; it simply alters the incoming waves so that the telephone can detect them.

An improved arrangement of the detecting circuit is shown in Fig. 1248. Here contact *C*, provides for tuning the antenna circuit, while the contact, *E*, permits of varying the coupling to the detector circuit. Furthermore, the telephone, *T*, is placed in series with the rectifying detector *D*, so that all of the alternations through the telephone in one direction are suppressed by the detector and in the other direction are permitted to flow freely.

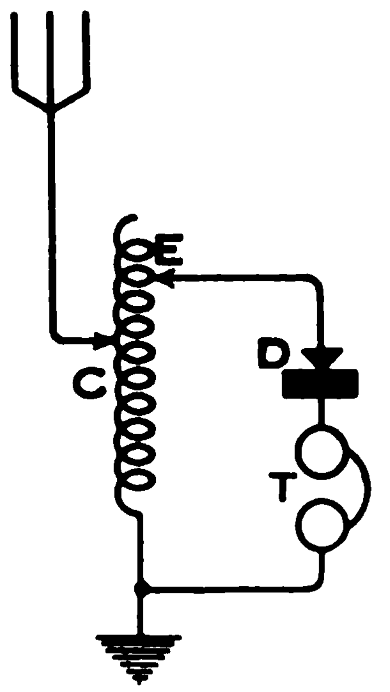

FIG. 1248.—Receiving circuit with crystal detector and provision for tuning.

Barretter.—The liquid barretter consists of a minute cup containing a drop of nitric acid in the center of which is mounted a piece of Wollaston wire, composed of silver, 3 or 4 mils in diameter with a core of platinum 0.1 of a mil in diameter. This forms the connecting link between the aerial circuit and the ground. The acid dissolves the silver away from the platinum and leaves a minute surface of platinum in contact with the acid. A small e.m.f. connected in series with a pair of head phones and shunting this contact, constitutes the receiving circuit. The e.m.f. is adjusted until the fine wire point which is connected to the positive side of the battery is able to evolve a bubble of oxygen gas on the tip of the wire. The e.m.f. is almost, but not quite, sufficient to rupture this bubble. When, however, a wave train oscillates in the aerial circuit, the bubble is ruptured and the resistance due to the gas disappears and the current rises and falls in the local circuit through the battery. The device was exceedingly sensitive, in fact, too sensitive for most commercial work, the difficulty being that the heavy currents entering the detector would often burn away the platinum point.

The Electron Tube

A widely used detector of radio waves is a form of electron tube called the **audion.** The connections for a receiving circuit with this gaseous detector are shown in Fig. 1249. A positively charged plate, *P*, is mounted in a vacuum tube, together with a heated filament, *F*, and a grid, *G*. The filament is heated by a local 6-volt storage battery *E*, while the battery *B*, usually of about 22 volts and adjustable, is used to energize the telephone

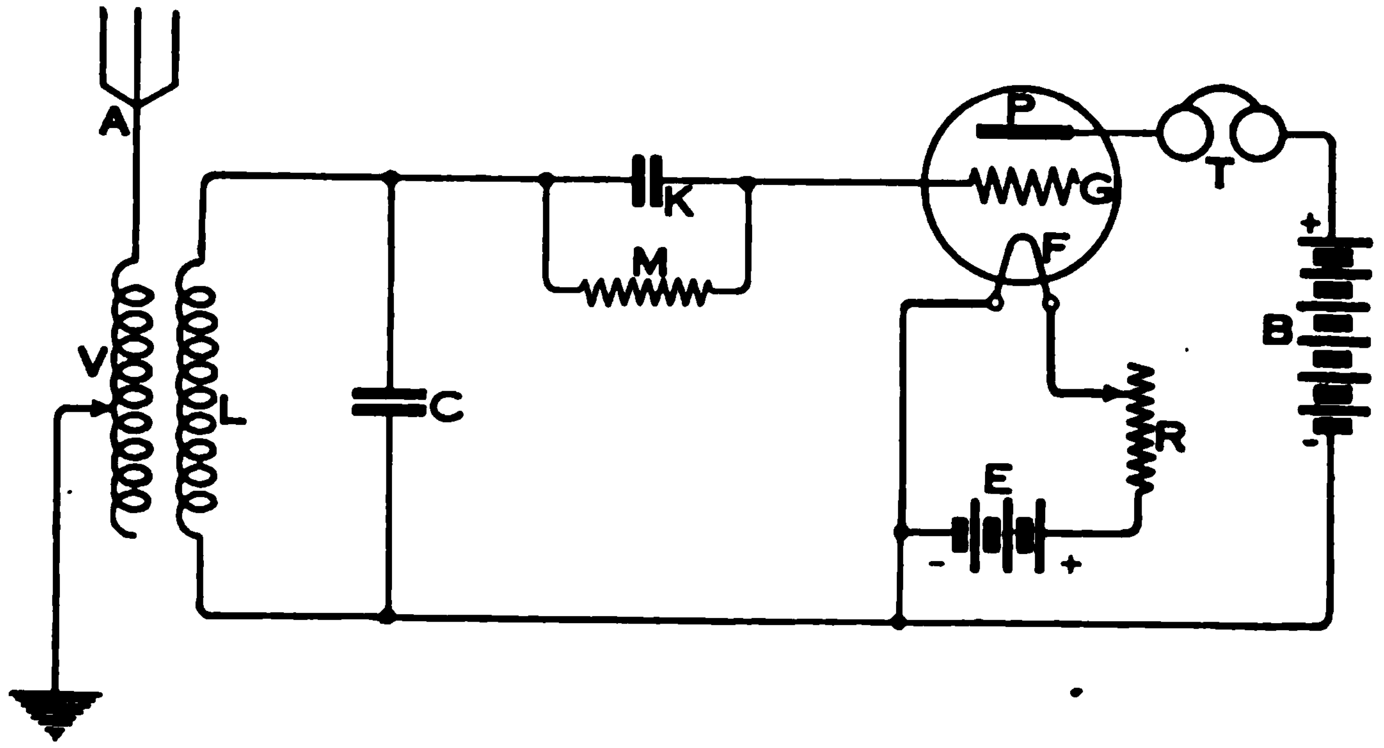

FIG. 1249.—Simple form of receiving circuit employing the audion electron tube as a detector.

receiver *T*. The aerial *A* is connected to the coil *V*, which is inductively coupled to *L*, and thus serves to supply impulses to the audion.

A filament heated to incandescence in a vacuum tends to give off streams of negative electrical charges or electrons. Now, when the filament is negative, the cathode stream of electrons emitted from it are drawn toward the plate anode, *P*, by the difference of potential across the bulb. These electrons, as they collide with the molecules of gas within the bulb, ionize them—that is, they render them conducting in the direction **from** the plate **anode** *P* **to** the filament **cathode**, *F*. When such an electron stream emanates from the heated surface of the filament *F*, it can be controlled by electric charges. The positively charged plate *P*, supported within the tube, will attract and intensify the stream of electrons, while a negatively charged plate or grid, *G*, will repel and weaken the stream.

By varying the potential impressed upon the grid *G*, the stream of electrons thrown off from the hot filament can be greatly altered. Passing through the holes in the grid, the electrons bombard the plate behind it and give up thereto their aggregate charge and current. When properly constructed and adjusted a relatively **small change** of electrical **potential** at *G* will produce a relatively **large change** in the intensity with which the plate *P* is bombarded and therefore in the strength of the current which will pass through the bulb from *P* to *F*, and thence to the negative terminal of the battery *B*. The high frequency oscillations in *L* are broken up into two sets of charges, one positive and one negative. These impulses charge *G* positively or negatively. If negatively they **decrease** the amount of current which can pass from *P* to *F*. If positively they **increase** the current which can pass from *P* to *F*, and therefore the current in the telephone receivers *T*. Thus as in the crystal detector, impulses in one direction are suppressed, while those in the other direction merge into one continuous impulse from every wave train and affect the telephone receiver accordingly.

Better results are often obtained by the insertion of a condenser, *K*, in the grid circuit. When this is used, it is desirable to place a high resistance, *M*, of from 1 to 2 megohms, called a grid leak, around the condenser. This is employed for the purpose of maintaining the grid at the proper potential with respect to the plate, by allowing the negative electrons which accumulate on the grid to leak away between the oscillations of the main current.

The great advantage of the electron tube as an amplifier of the minute incoming signals, lies in the fact that a **comparatively small change** in the **potential** of the **grid** will bring about a **relatively large change** in the **current** flowing **through the tube,** from the plate to the filament. When the filament is heated to its proper temperature it has been found that **one volt added to the potential of the grid** *G*, **will make eight times as much change in the plate current as one volt added to the plate voltage of** *B* **would make.** This principle, which represents the relative effect of the grid voltage and plate voltage upon the plate current, is called the **amplification coefficient** of the tube.

Audion Detector and One-Step Amplifier

Fig. 1250 shows how the simple detector circuit shown in Fig. 1249 may be improved by adding one or more stages of amplifica-

tion. The detector portion of this circuit is the same as in Fig. 1249, except that the telephone, *T*, is replaced by the primary, *I*, of an induction coil with an iron core, *C*, having a ratio of approximately one to six. The secondary, *S'*, of this induction coil now takes the place of the secondary, *S*, of the vario-coupler, *VC*, connected to the antenna circuit, and is employed to energize the grid, *G'*, of a second tube. As a slight variation in potential of *G* causes a considerable variation in the current from *P* to *F*, this will bring about a magnified variation in the potential of *G'*. This in turn will cause a still further magnified effect upon the

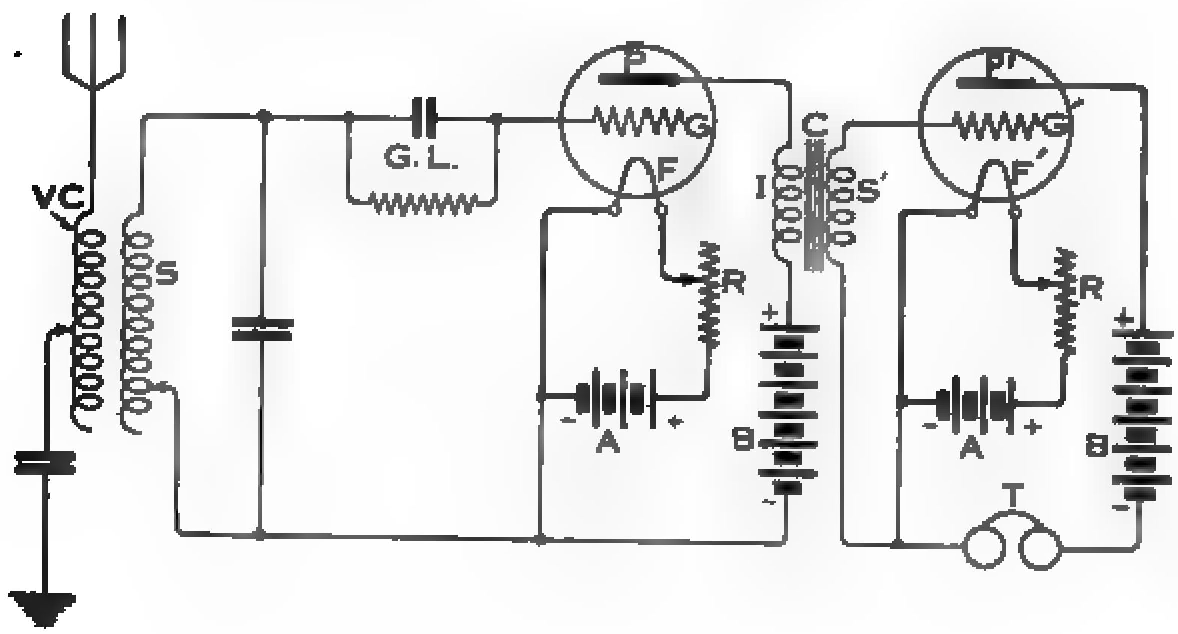

Fig. 1250.—Receiving circuit with audion detector and one-step amplifier.

current from *P'* to *F'* and will consequently greatly magnify the effect on the telephone at *T*. Sometimes not only two, but three, four, five or more steps of amplification are employed. The same storage battery may be used to energize all of the filaments, and under certain conditions the same *B* battery may be used for all of the plate circuits. It is preferable, however, to use separate plate batteries.

Armstrong Regenerative Circuit

The sensitiveness of an electron tube as a detector may be enormously increased by a method which multiplies its amplifying action. This action was discovered by Armstrong, and is the basis of his **feed back**, or **regenerative** circuit. Fig. 1251 illustrates the principle of this regenerative action. When oscillations are induced in the circuit *A-L-C*, a varying potential is applied through the condenser, *K*, to the grid *G*. As already

explained, this varying potential produces a corresponding variation in the current which flows from the battery *B*, through the plate *P*, to the filament *F*, and thence through coil *E* and the telephone *T*. The coils *E* and *A* are inductively coupled, and this plate current, on its way through *E*, by means of mutual induction, transfers some of the energy of the plate oscillations back into *A*, thereby boosting the current in the circuit *A-L-C*. This produces amplified variations in the grid potential, which in turn produces still higher variations in the plate current, thus still further reinforcing the oscillations of the system. Simultaneously

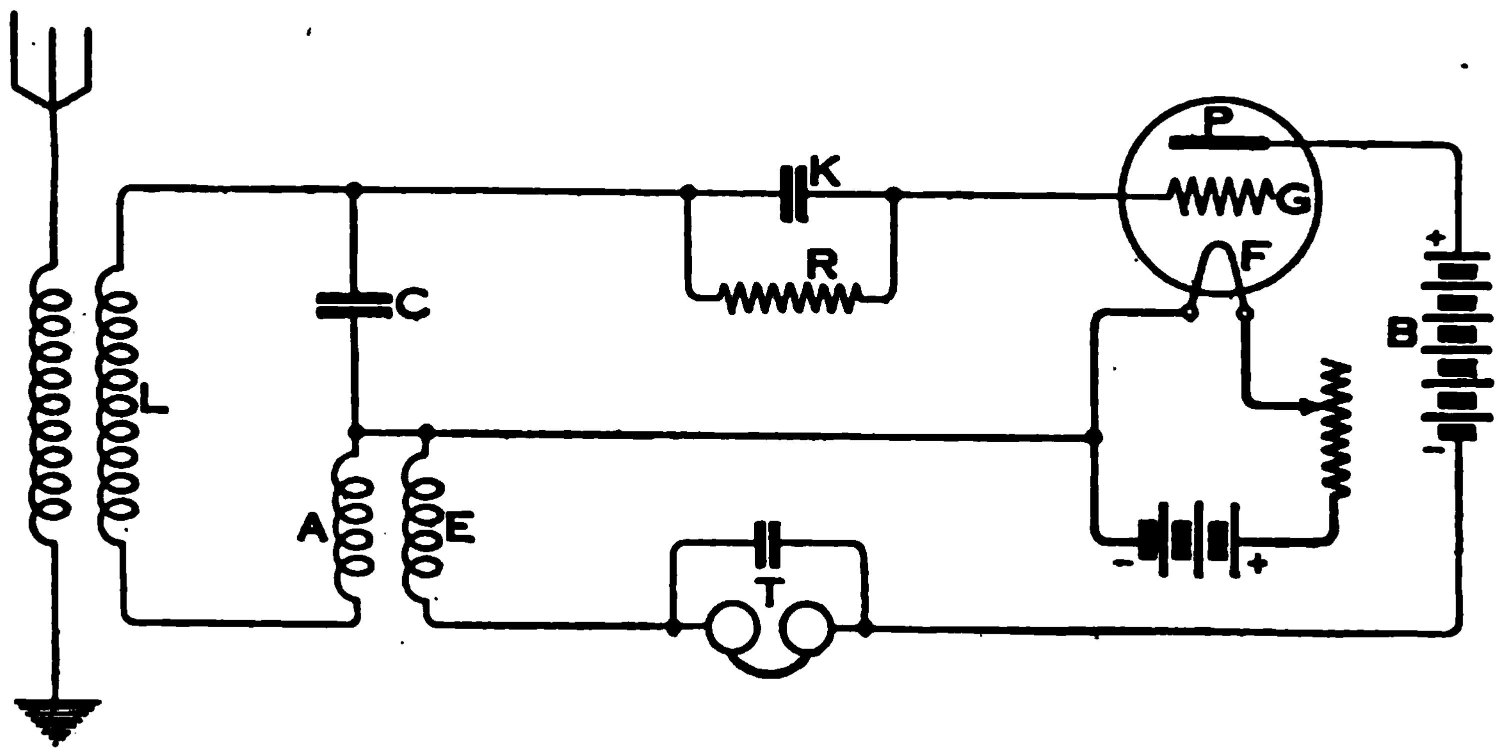

FIG. 1251.—Receiving circuit with audion detector and Armstrong "feed-back" or "regenerative" circuit.

with this amplification, the regular detecting action goes on. The condenser, *K*, is charged in the usual way, but accumulates a charge which is proportional, not to the original strength of the incoming signal, but to the final amplitude of the oscillations in the grid circuit. The result is a current in the telephone much greater than would have been obtained from the original oscillations in the circuit.

The Electron Tube as a Generator of Oscillations

The electron tube can be made to generate high-frequency currents and thus act as a source of radio currents for the transmission of signals. **Any regenerative circuit, such as that shown in Fig. 1251, can be made to generate spontaneous oscillations, provided it be so arranged that any change in grid voltage, *G*, makes a change in plate current, *P*, of such magnitude that there is induced in the grid circuit a larger voltage than that originally acting.**

An alternating current is said to be **modulated** when the amplitude of its oscillations is varied periodically. The frequency with which the variations occur is necessarily less than the frequency of the alternating current which is being modulated. The subject of modulation of radio frequency currents radiated through space constitutes radio telephony. Fig. 1252 represents the wave form

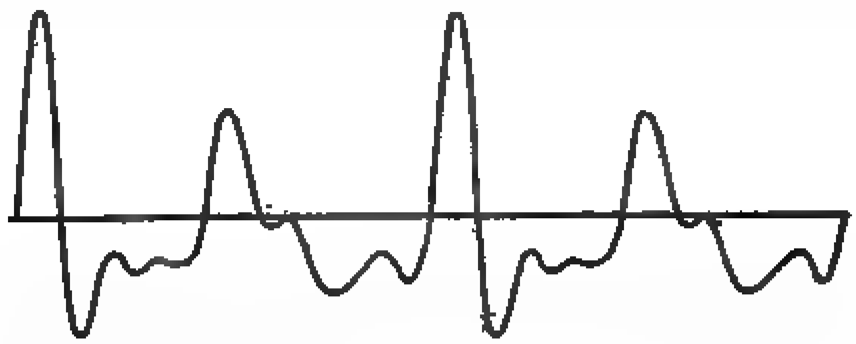

FIG. 1252.—Variation of current in wire telephone circuit when the sound "a," as in "starter," is spoken into the transmitter.

of current on a telephone line transmitting the sound of "a" as in starter. Fig. 1253 represents a continuous undamped wave train from an oscillating source, Fig. 1254 represents the antenna

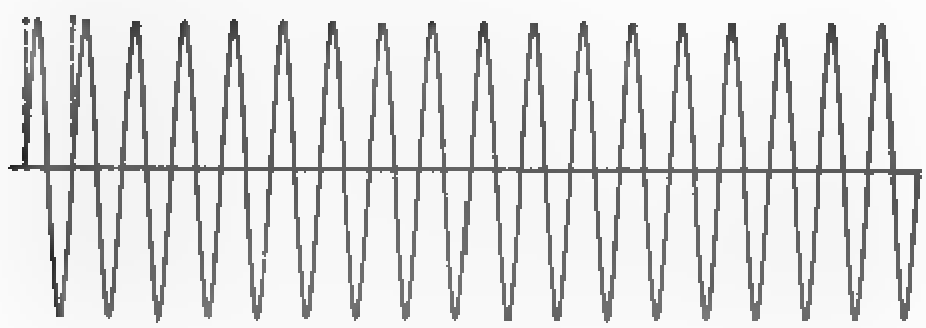

FIG. 1253.—Undamped wave train at radio frequency generated in oscillating circuit.

current in radio telephony, transmitting the sound "a" as in starter, resulting from the superimposing of the telephone current upon the continuous radio frequency wave, thereby giving the modulated radio frequency wave shown, which can be received with a simple detector. The most common method of tube modulation for radio telephony is by variation of the power input through the plate. The general scheme is shown in Fig. 1255. The apparatus within the dotted lines, *W-X-Y-Z*, represents the system for **generating oscillations** at **radio frequency**, the main current being supplied from a high voltage battery, *B*, or from a D. C. generator connected to the points *E*+ and *E*−. The apparatus for **modulating** these oscillations at voice or **audio frequency** is embraced within the dotted lines *H-I-M-N*. The potential of the grid, *G*, in the modulating tube is varied by con-

necting the secondary, S, of the induction coil or transformer energized from the transmitter and battery, between the grid, G, and the filament F. Now, when sound waves enter the transmitter T, the current in the primary of the induction coil supplied by the local battery rises and falls. This induces alternating e.m.fs. in the secondary, which alter the potential of the grid, G. The battery, B, furnishes a current through the inductance L, which is fixed in amount by this inductance, and which divides

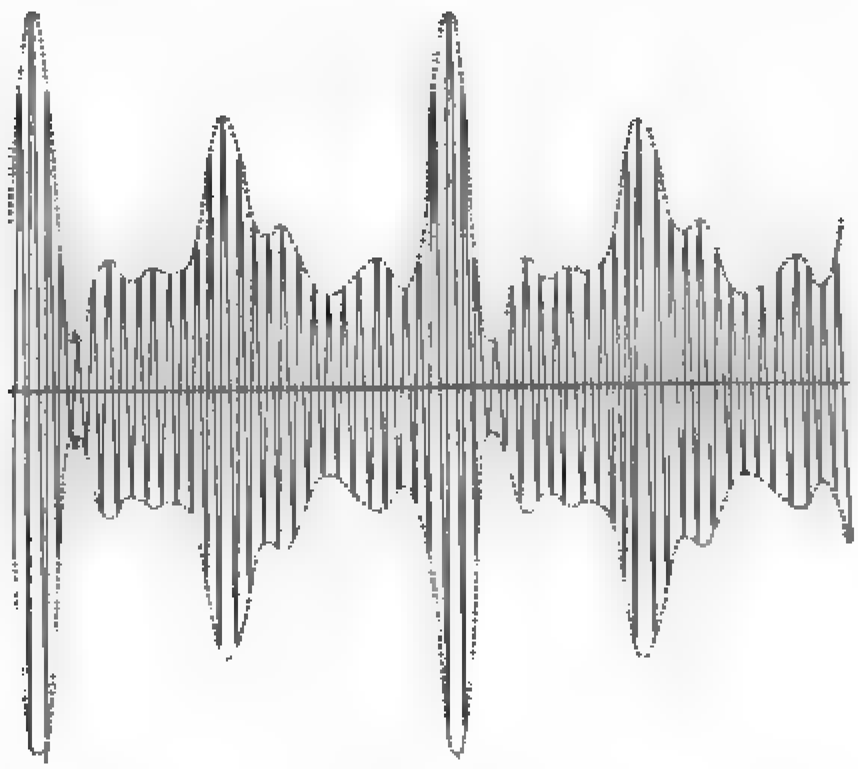

FIG. 1254.—Modulation effected by superimposing the current produced by the sound "a," as in "starter," when spoken into a telephone transmitter, at audio-frequency, upon the alternating current in the oscillating circuit at radio frequency.

between the plate, P, in the modulating tube and plate P' in the oscillating system. Due to the properties of the generating system, oscillations at radio frequency are constantly going on in the circuit, $E+R\text{-}P'\text{-}G'\text{-}F'\text{-}E-$. When the potential of the grid, G, alters, the current through the path, $P\text{-}G\text{-}F$, alters. As the total current through L is fixed by this iron cored inductance, any alteration through P causes an inverse alteration through P'. This effect of the variation of the voice currents originating at T is superimposed upon the radio frequency currents in the oscillating circuit $E+$, $R\text{-}P'\text{-}G'\text{-}F'\text{-}E-$, and is repeated through the inductive coupling into the transmitting antenna.

To sum up this action: The variations at speech frequency in voltage of the grid, G, cause variations at speech frequency in the

resistance of this tube. Since the sum of the tube current plus the load current remains constant, due to the inductance L, the load voltage and the load current pulsate at speech frequency. This load voltage and load current from the modulator tube constitute the power supply to a generating system, in which the

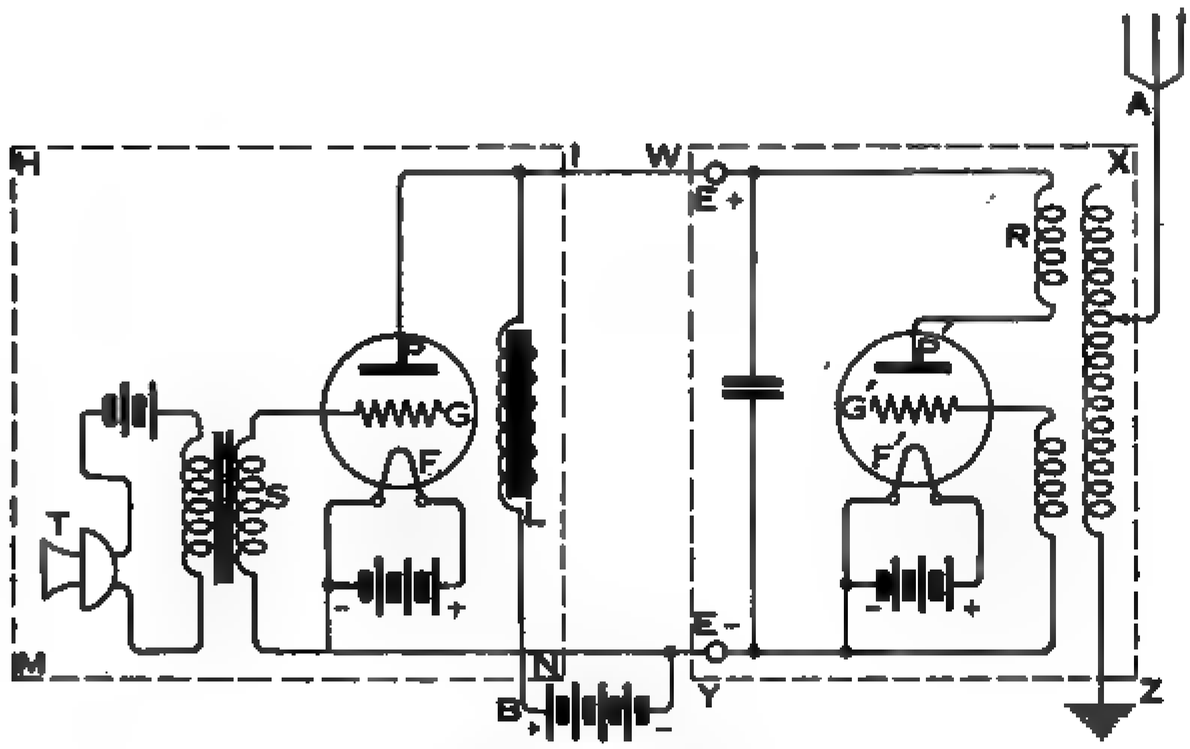

FIG. 1255.—Complete modulating and oscillating circuits for radio telephone transmitting station.

antenna current is approximately directly proportional to the supply voltage. Therefore the radio frequency output at A, is modulated at speech frequency and the variation in the radio wave emitted causes an audio frequency tone in the receiving apparatus, corresponding to the tone impressed on the microphone of the transmitting circuit.

Loud-Speaking Receiver

Fig. 1256 illustrates a form of loud-speaking receiver employed to magnify the reproduction of sound for use at large public gather-

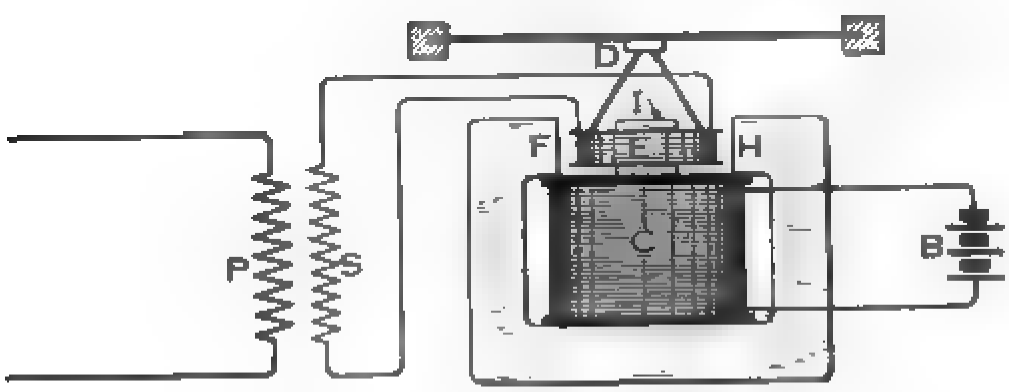

FIG. 1256.—Form of loud-speaking receiver for magnifying telephonic reproduction for large audiences.

ings. Here an electromagnetic, C, energized from a 6-volt storage battery B, is employed to produce a powerful magnetic field between the pole I and the poles F-H, in an almost completely closed magnetic circuit. In a narrow gap at the top is suspended an extremely small and light coil E, which is rigidly attached to the center of an aluminum diaphragm, D, which itself is mounted in a fixed position at its circumference. This floating coil is supplied with current from the secondary, S, of an induction coil, the primary of which, P, receives the talking currents. A great amplification of sound is produced over that obtained in an ordinary telephone receiver.

SECTION XXIII — CHAPTER IV

TELEGRAPHY

RADIO TELEGRAPHY AND TELEPHONY

1. Explain the object of the oscillator in wireless telegraphy. How is it constructed? Sketch.
2. Mention the principal detectors of radio signals which have been employed.
3. Explain the principle of the "crystal" detector. Sketch simple circuit.
4. Explain the principle of the "liquid" detector. Sketch simple circuit.
5. Explain the principle of the "audion" detector. Sketch simple circuit.
6. Explain the principle of the audion as an amplifier.
7. Explain the "Armstrong regenerative" circuit. Sketch.
8. Explain the principle of the audion as a generator of electric oscillations. Sketch simple circuit.

ILLUMINATION

INCANDESCENT LAMPS

The carbon filament incandescent lamp is the invention of Thomas A. Edison. The original patent was dated January 27, 1880, and covered a filament of paper or carbonized cellulose mounted in an all glass hermetically sealed vacuum chamber with platinum leading-in wires. The filament was of high resistance and was adapted for the distribution of current through a large number of lamps in multiple.

The Carbon Lamp.—Following this original lamp, Edison selected bamboo fiber as the most suitable material from which to make filaments. This was followed by a cellulose filament made from cotton and subsequently carbonized. Oxygen being necessary to combustion, the exclusion of the air prolonged the life of the filament. Carbon being very refractory in character could be worked at a temperature of from 1,700 to 1,900 degrees Centigrade without rapid disintegration.

Light may be obtained electrically in two ways:

First, through the medium of incandescence.

Second, through the medium of luminescence.

In the first place light is a temperature effect and a high temperature is essential to any degree of efficiency.

In the second place there is a direct transformation of the electrical energy into light without passing through the medium of heat.

To insure uniform conductivity the process of **flashing** the filament was devised. This consisted in depositing carbon upon the filament from some liquid or hydro-carbon vapor so that a uniform conductivity was insured. The original filament required four watts to produce a candle power. Subsequent improvements reduced consumption to 3.1 watts per candle power.

The GEM Lamp.—Following the carbon lamp, the **GEM** lamp was produced by the General Electric Company. This contained a **metalized** filament, which was made by subjecting a carbon filament, both before and after flashing, to a high tem-

perature in an electric furnace. The term "metalized" was applied because of the positive temperature coefficient which was acquired during the process. Carbon normally decreases in resistance with a rise in temperature. After this special treatment, however, it changes its nature and has a positive temperature coefficient. These lamps consumed but 2.5 watts per candle power because of the higher temperature at which the filament could be worked.

The Tantalum Lamp.—In 1907 the **Tantalum** lamp appeared. This consisted of a filament of metallic tantalum which had a very high melting point and could therefore be worked at a higher temperature than carbon. Because of the low specific resistance of Tantalum the filament was about 2 feet long for a lamp consuming 44 watts. The higher temperature gave an efficiency of 2 watts per candle power. As the metallic filament possessed a positive temperature coefficient, a rise in voltage was not accompanied by a corresponding rise in current. The carbon filament, however, falls in resistance when the e.m.f. is raised and the current tends to overtax the lamp; thus an increase of 5% in voltage on a carbon filament lamp will under certain conditions cause an increase of 40% in light.

The Tungsten Lamp.—Soon after the appearance of tantalum, the tungsten lamp was produced. Tungsten is a still more refractory metal than tantalum. It will melt only at a temperature of from 3,000 to 4,000 degrees Centigrade. Because of the difficulty of reducing it, the early filaments were constructed by reducing tungsten compounds or oxides to powder and mixing them with binding material after which they were pressed into the filament shape and subsequently heated to drive off foreign materials. These filaments were exceedingly frail. Shortly thereafter the drawn-wire filament lamps were produced.

To produce wire-drawn filaments, the following process was developed:

Oxide of Tungsten in a finely powdered form was mixed with a binder and subjected to hydraulic pressure. In this way small rods approximately 1/8 inch long were formed. These were placed vertically in porcelain tubes between the terminals of an electric circuit. As tungsten is very oxidizable it was necessary to send a stream of hydrogen gas through the tube to prevent the oxidation of the rod. An alternating current of 700 amperes at 9

volts was then applied. The heat generated was sufficient to drive off the impurities and produce a rod of pure tungsten which, however, was of a very crystalline and fragile character. This rod was then passed through a swaging machine which simultaneously hammered it on all sides and lengthened it out into a wire about 30 feet long. This process greatly increased the ductility of the metal so that it could be finally drawn through diamond dies similar to those used for drawing copper and other wires. The dies were of constantly diminishing cross-section and this rod finally yielded a wire 1,000 feet long of proper cross-section for 40-watt lamps.

Lamps of this size are exhausted to a moderate vacuum, as are carbon lamps. In sizes of 100 watts and upwards the lamps are filled with argon or nitrogen gas. A vacuum lamp has a tendency to blacken due to the deposition of the condensed vapor of tungsten thrown off by the heated filament. If the pressure within the globe is raised, the vaporization will be restrained. It was therefore found desirable to introduce an inert gas which would not combine with the filament, at a pressure just below the atmosphere so that when the gas is heated the expansion will bring about a pressure within, which is practically equal to the pressure without. As a consequence the filament may be worked at a higher temperature than formerly. This results in a greater economy. A carbon filament lamp will give 40 times as much light at 2,000 as at 1,900 degrees. Once the filament is brought to the incandescent state any further increase in temperature is accompanied by the production of a large amount of light with a very small increase in consumption of power. Gas filled lamps therefore are much more economical and superior in every way to the vacuum lamps. A 40-watt vacuum tungsten lamp has an efficiency of 1.25 watts per candle power. Gas filled lamps have an efficiency, in sizes of from 100 watts to 200 watts, of 1 watt or less per candle power. With concentrated filaments of a spiral character for low voltages, designed for moving picture projection, efficiencies as high as 0.4 watt per candle power have been obtained.

Platinum leading-in wires have been discarded even in the smaller sizes and special alloys have been substituted which have the same coefficient of expansion as glass.

The word **Mazda** is a trade mark representing the highest

standard of quality in metallic filament lamps. It is the seal or brand of a plan of exchange of information between associated lamp manufacturers. As all other types of incandescent lamps except tungsten have practically been discarded the name has come to represent the highest standard of perfection in tungsten lamps.

SECTION XXIV CHAPTER I

ILLUMINATION

INCANDESCENT LAMPS

1. Explain the construction and efficiencies of the carbon and G. E. M. incandescent lamps.
2. Explain the construction and efficiency of the Tantalum incandescent lamp.
3. Explain the construction and efficiency of the Tungsten vacuum lamp
4. Explain the construction and efficiency of the Tungsten gas filled lamp.

ILLUMINATION

ARC LAMPS

In 1810 Sir Humphrey Davy produced the first arc light. The Royal Society of England presented him with £1,000 with which to experiment. He constructed two thousand cells of plunge battery and connected these to terminals of two small pieces of wood charcoal as in Fig. 1257. When the pieces of charcoal were brought within a short distance of each other the current passed, heating the charcoal to incandescence. When the electrodes were separated the current continued to pass on

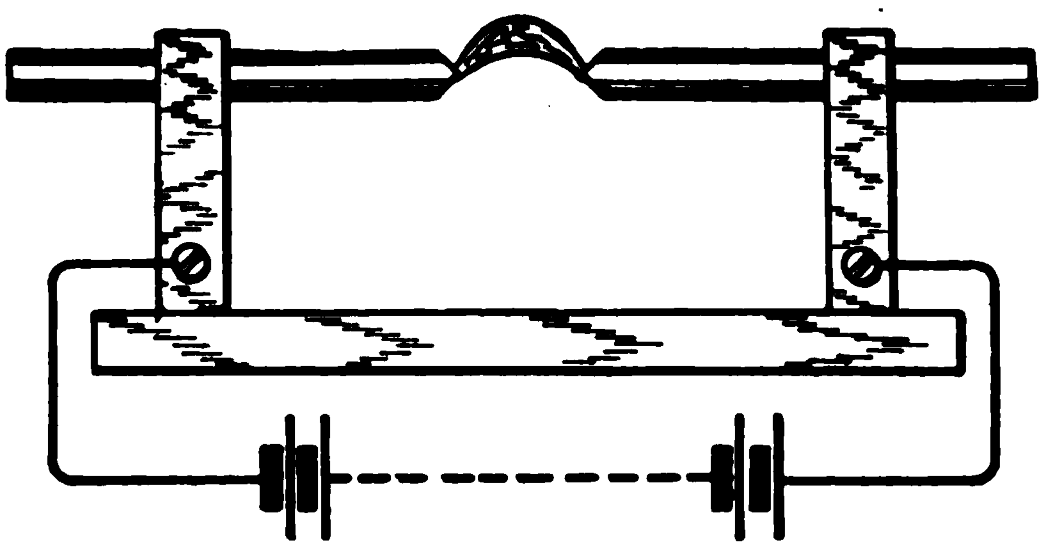

FIG. 1257.—Sir Humphrey Davy's arc light.

the conducting vapor in a beautiful as-ending arch of light. This was therefore called the **arch** light. The name was subsequently shortened to **arc** light.

The carbon arc is the oldest form of street illuminant. A current of about 10 amperes under a pressure of about 50 volts passed between two electrodes of hard carbon about one-half inch in diameter separated from 1/8 to 1/4 of an inch. The upper carbon was made the positive electrode. The current causes particles of the end of the positive carbon to be heated to incandescence and then vaporized, forming a conducting path of carbon vapor between the two electrodes. On this path the current flows. The positive carbon is very much hotter than the negative. The temperature of the terminal of the positive carbon is approximately 3,500 degrees Centigrade. The end of this electrode becomes hollowed and forms a crater. Eighty-

five % of all the lights given by the arc come from this spot The temperature is so high that the intrinsic brilliancy of the crater is 8,000 times that of an incandescent carbon filament at 1,800 degrees Centigrade The carbon vapor is carried across to the negative electrode where it condenses and is deposited in the form of a nipple The positive carbon burns away about twice as fast as the negative Fig 1258 shows the appearance of an open carbon arc The refractory nature of the carbon accounts for the high temperature at which it may be worked before volatilization occurs.

FIG. 1258.—Actual appearance of crater and nipple in carbon arc light

In order that the electric arc may be used commercially, a mechanism must be provided, first, for separating the carbons and striking the arc, and second, for feeding them together as they burn away.

Carbon Arc Lamps

The first automatic arc lamps were designed by Charles F. Brush in 1878 The general construction of the mechanism of an arc lamp is shown in Fig.1259. This is a differential arc lamp and may be used on any kind of a direct-current source. Current passes in at the positive terminal, thence through the series magnet, *Se*, and through the rod *A* which carries the upper carbon, thence via the bottom carbon to the negative side of the line. There is a by-path through the shunt magnet *Sh* which is of comparatively high resistance As this path is virtually short-circuited by the path through the series magnet and arc, the shunt magnet is not energized The series magnet therefore pulls up on the core, the clutch mechanism *C* is locked and the upper carbon holder and carbon are raised As the pressure across the terminals of the lamps is about 50 volts, the current continues to flow across the gap as the arc is struck As the carbons burn away two results ensue The lengthening arc is accompanied by an increase in resistance which causes the

current in the arc to fall The series magnet therefore becomes weaker. At the same time the shunt magnet which is across the arc is subjected to the potential of the arc which rises as the gap lengthens. There is, therefore, a simultaneous weakening of the series magnet and strengthening of the shunt magnet. This soon disturbs the mechanical balance and causes the shunt magnet to overpower the series magnet The shunt magnet therefore pulls down on its core, releases the clutch and permits the positive carbon to feed by gravity toward the negative. Before it can reach the negative, however, the shortening of the arc, accompanied by the reduction in resistance, causes the current to rise, the series coil is strengthened, the potential across the shortened arc falls and causes a reduced effect upon the shunt magnet, and the series magnet regains control, draws up the armature, locks the clutch and checks the further descent of the carbon Thus means are provided for feeding the carbons together as required.

On constant potential circuits the shunt magnet is not absolutely necessary. A spring may take the place of this magnet as shown in Fig. 1260. Here the series magnet operates as before to strike the arc. When the arc becomes sufficiently long the current falls in the series magnet to such an extent that the spring *S* is able to overpower it.

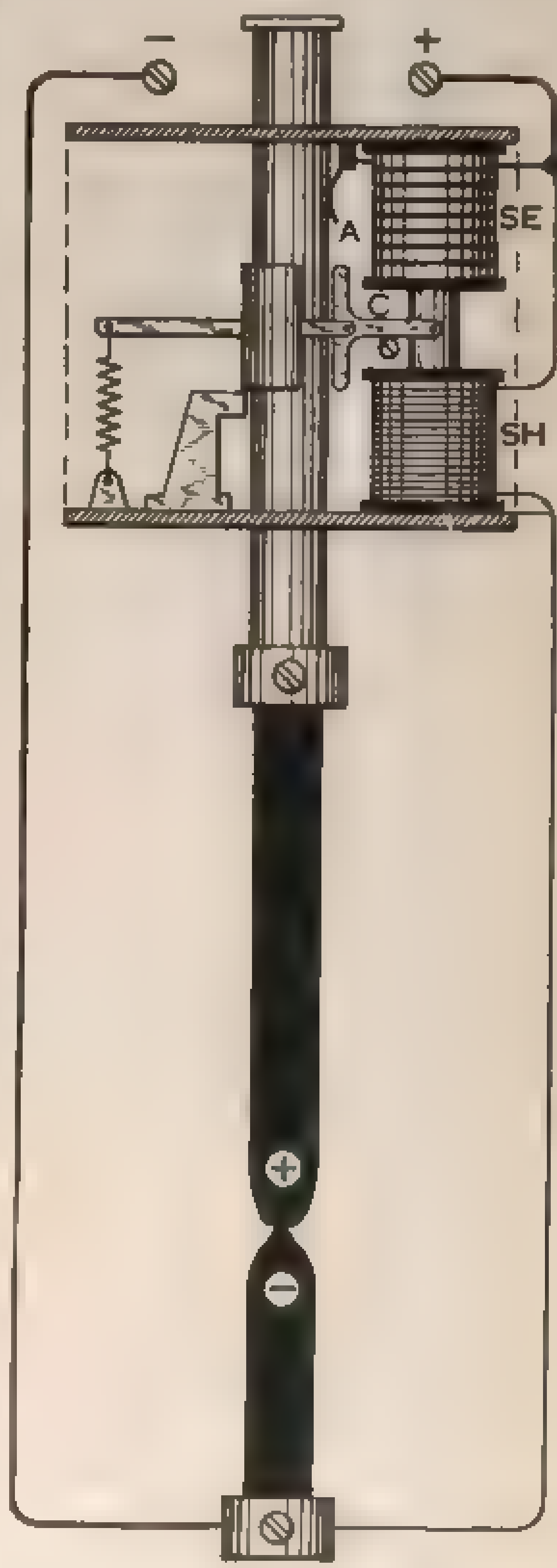

FIG. 1259. Differential arc lamp for constant-potential or constant-current circuits.

pulling down on the core and releasing the clutch, allowing the carbons to drop together When they do so the resulting

FIG. 1260 —Series arc lamp for use singly, on multiple circuits only.

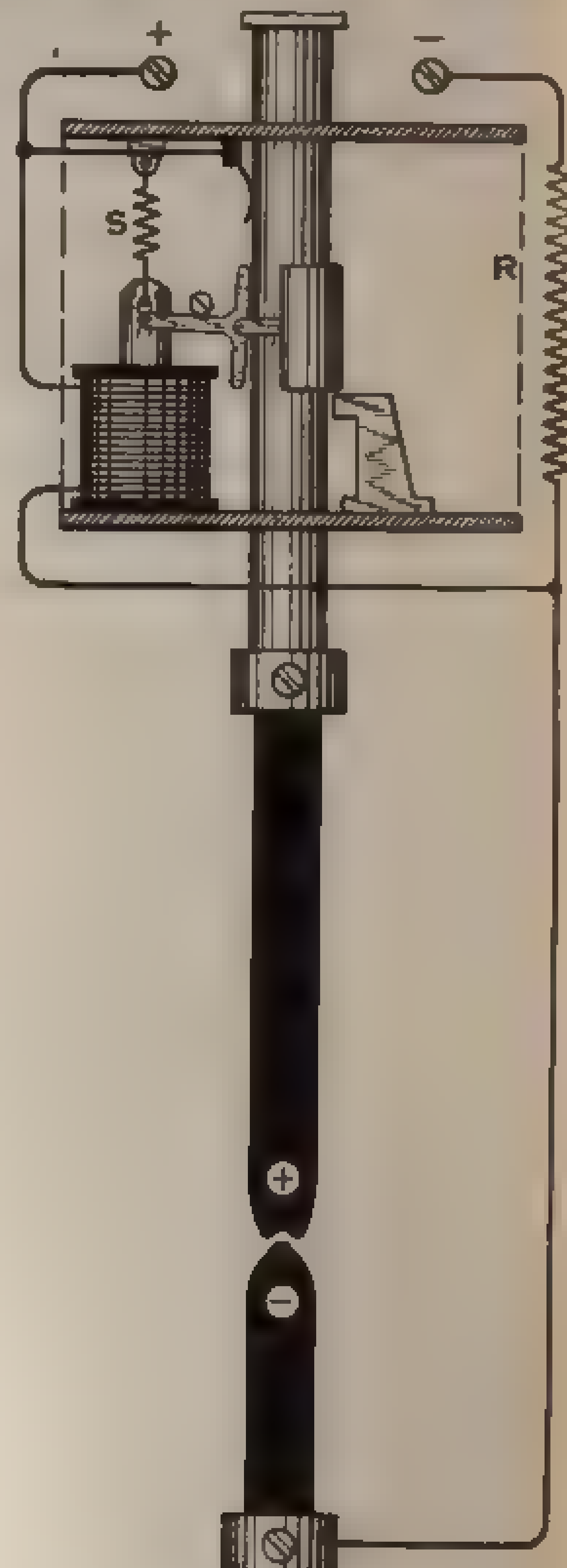

FIG. 1261 -Shunt arc lamp used at one time, in series groups, on constant potential circuits only

increase in current strengthens the series magnet which overpowers the spring, causes the clutch to again lock and the arc

to be restruck. The feeding is not as smooth as in the differential lamp but this simple construction has proved very satisfactory on multiple systems.

At one time the shunt lamp shown in Fig. 1261 was employed for series groups, on multiple circuits. Here a spring *S* replaced the series magnet. The carbons were normally held apart, the clutch being in the locked and raised position due to the spring. When the current was applied it could not pass through the gap, for the carbons were separated. It therefore took the alternative path through the shunt magnet. This overpowered the spring, unlocked the clutch, and the carbons dropped together. This formed a virtual short circuit on the shunt magnet which was thus de-energized, the spring was then free to act, to lock

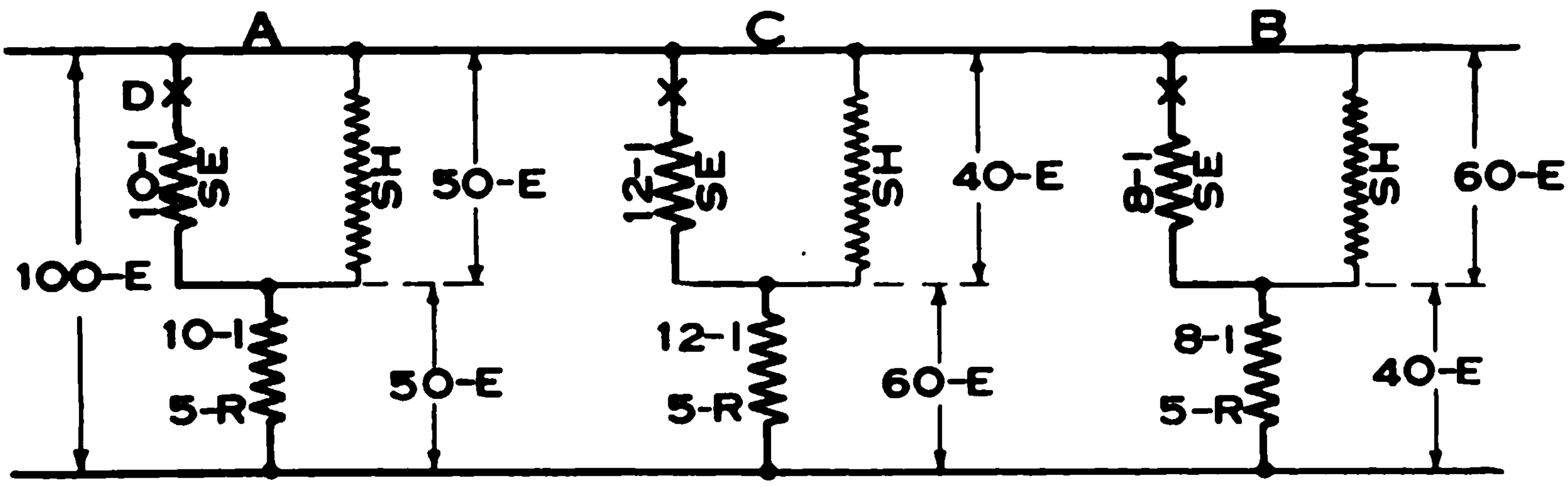

FIG. 1262.—Regulating principle of series and shunt magnets in differential arc lamp on constant potential circuits with ballast in series.

the clutch and strike the arc. Like the lamp with only the series magnet this lamp was not as smooth as the differential lamp in its operation.

A ballast resistance, *R*, is required in series with all arc lamps worked on constant potential circuits. The object of this ballast is two-fold: First, without it the electro-motive-force at the terminals of the shunt coils would be constant and the lamp could not feed for there would be no way of varying the potential on the shunt coil. Second, the ballast is necessary to steady the action of the arc. The resistance of the arc decreases with an increase of current. Therefore it would be impossible to maintain a steady arc on a constant potential circuit without an appreciable resistance in series with it.

To understand the action of the ballast, consider Fig. 1262. Here the arc is shown at *D*, in sketch *A*, the series magnet *Se*, and the shunt magnet *Sh* and a ballast of 5 ohms in series across a

100-volt line. The drop in potential across the shunt magnet and arc is 50 volts. Assuming the arc to take a current of 10 amperes, this current will pass through the 5-ohm ballast and also cause a drop of potential of 50 volts. Now suppose the carbons burn apart and the current falls in the arc to 8 amperes due to the increased resistance, as shown at *B*. Eight amperes passing through 5 ohms ballast causes a drop of only 40 volts. As the line pressure is 100 volts this raises the pressure on the shunt magnet to 60 volts. The current in the series coil having fallen to 8 amperes, and the shunt coil having its pressure raised to 60 volts, insures that the shunt magnet will overpower the series magnet and cause the clutch to be released and the lamp to feed. Should the carbons drop too close together the condition shown at *C* will result. The current may now run up to 12 amperes through the arc and series coil. But 12 amperes in the 5-ohm ballast brings about a drop of 60 volts which leaves only 40 volts to be impressed upon the shunt magnet. The shunt magnet now becomes very weak and the series magnet very strong. The series magnet therefore overpowers the shunt, locks the clutch and lengthens the arc. As the source maintains a **constant potential** it will be evident that a **series ballast** is **essential** in order to obtain a **variable potential** on the shunt coil.

The Metallic Flame Arc

The open carbon arc has an efficiency of about one watt per candle power. An improvement in efficiency is found in the metallic flame arc designed for D. C. circuits. The construction is radically different from the open carbon arc. Instead of employing a positive electrode which is volatilized, the positive consists of a copper block *C*, Fig. 1263, while the negative electrode *M* is the one which is vaporized and is fed upward from the bottom. The negative electrode consists of an oxide of iron powder, called magnetite, mixed with chromium and titanium salts, and packed in an iron tube. The current volatilizes the magnetite and produces a long arc. The vapor of iron oxide being a good conductor, the arc is stable at all temperatures. The magnetite, however, is not very efficient as a light producer. The volume of the conducting vapor supplied by the magnetite is more than is necessary, hence oxide of chromium is added to restrain evaporation. The light comes from the flame of the arc and not from the electrodes, the high efficiency being due to the

salts of titanium which are contained in the negative electrode and which are automatically released and raised to a high degree of luminescence in the flame. The positive electrode, because of its large cooling surface, is consumed very slowly and will burn several thousand hours before it becomes so pitted as to require renewal. The negative electrode has a life, depending on its length, of about 200 hours. The lamps give off considerable smoke due to the vapor generated, making it un-

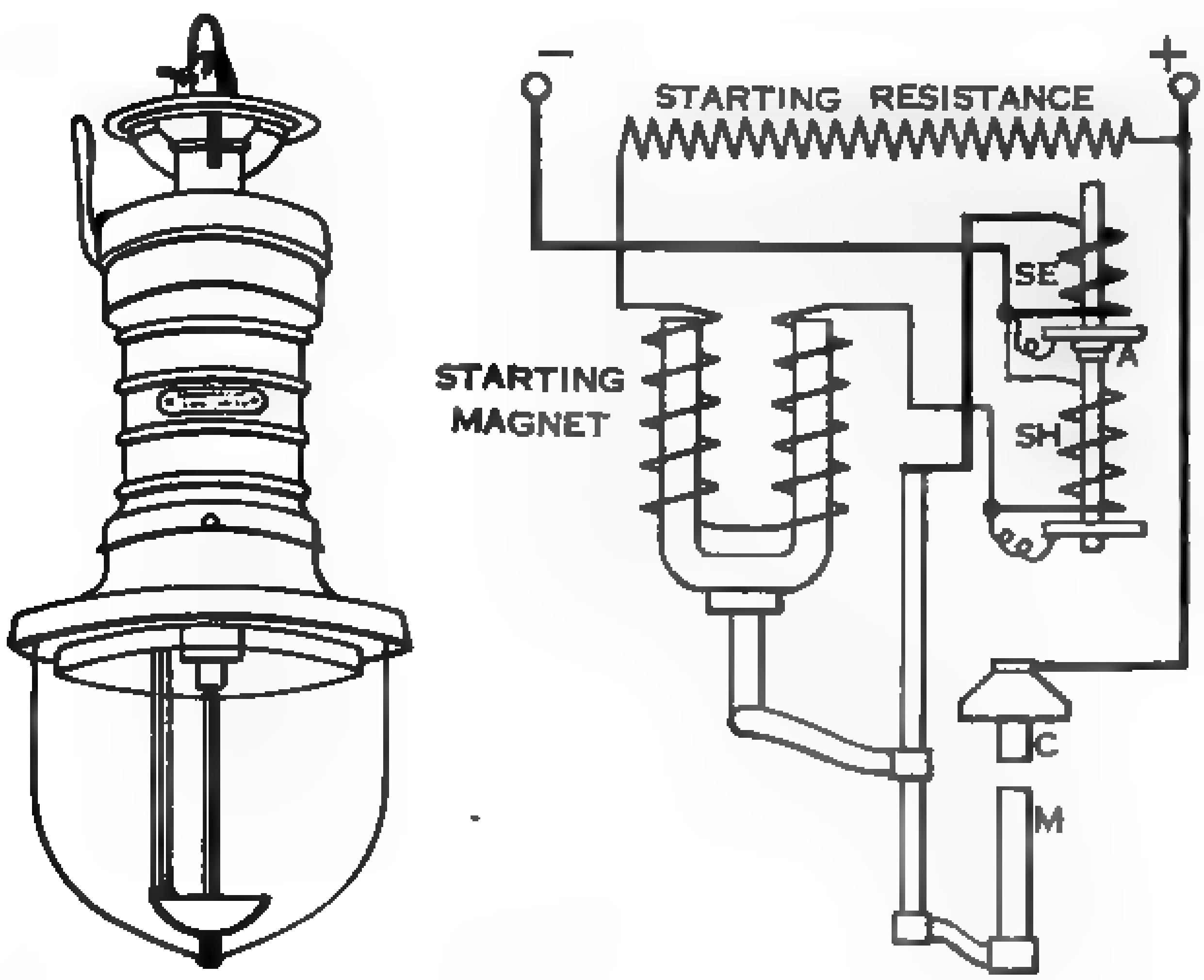

FIG. 1263.—Magnetite arc lamp built by the Westinghouse Company.

suitable for use indoors. It is, however, adapted for lighting of main thoroughfares in cities where its high efficiency of 0 5 watt per candle power gives it a distinct advantage. These lamps are made in two sizes, one requiring 4.0 amperes at 90 volts and the other 6.6 amperes at 80 volts. The latter has an efficiency of 0.3 watt per candle power.

The Flaming Arc

Some years ago the flaming arc was used to a limited extent for spectacular illumination. It will work on either A.C. or

D.C. circuits. The light is due to minute burning particles in the flame of the arc, which are raised to a high state of luminescence. The high efficiency of the light is due to the impregnation of ordinary carbon with calcium fluoride, which, in the arc, becomes intensely luminous. Some of the lamps were made with both of the carbons pointing downward inclined at an angle to each other, the arc flame being produced across their lower extremities. The light was usually intensely yellowish in color. The efficiency was extremely high, but 0.1 to 0.2 watt being required per candle power. It was impractical, however, to build these lamps for less than five or ten thousand candle power. They gave off great volumes of smoke and the arc was very unstable. They were used for a time in the illumination of theater fronts and in similar places but have generally been superseded by high candle power gas filled tungsten lamps.

The Mercury Vapor Arc

The mercury vapor lamp was devised by Peter C. Hewitt in 1901. It is usually built in the form of a vacuum glass tube about 1½ inches in diameter by 2 feet long, containing two electrodes, the negative electrode consisting of a well of mercury.

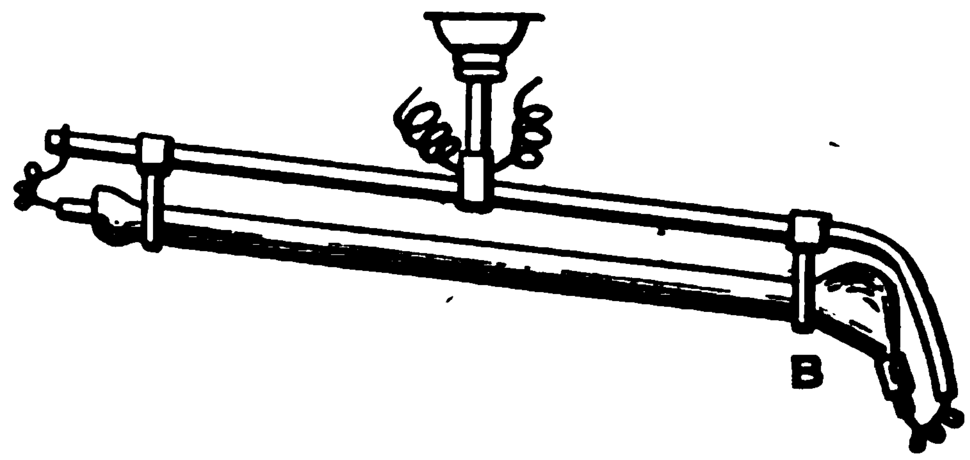

FIG. 1264.—Cooper-Hewitt mercury arc lamp.

The general appearance of the lamp is shown in Fig. 1264. It is employed on 110-volt circuits in series with a ballast of resistance and reactance to limit and steady the current. To start the lamp it is tilted until the mercury runs along the glass and connects the two electrodes. When this closed circuit is interrupted an arc is formed and the mercury vaporizes. On this conducting path the current continues to flow between the electrodes, raising the vapor to a high degree of incandescence. The mercury is constantly vaporized, re-condensed as it strikes

the cool walls of the tube and runs back into the well at B, whence it is vaporized over again. The peculiarity of the light is that it includes all of the rays of the solar spectrum except red. While it makes a highly efficient light by which to work and is not injurious to the eye, it nevertheless gives serious distortions in color values. It is used considerably for photography and is sometimes utilized in combination with incandescent lamps for modifying the color effect. The life of the bulb is about 1,000 hours and the efficiency is about 0.4 watt per candle. This lamp, like the open arc and enclosed arc, has been largely replaced by the high-power tungsten gas-filled lamp which has equal or better efficiencies and more satisfactory color values.

SECTION XXIV CHAPTER II

ILLUMINATION

ARC LAMPS

1. Explain the principle and efficiency of an open carbon arc lamp.
2. Explain the mechanism and operation of a differential arc lamp.
3. Explain the mechanism and operation of a series arc lamp.
4. Why must a ballast be used in connection with an arc lamp on a constant potential circuit?
5. Explain the principle of the "metallic flame" arc lamp. To what is the high efficiency due?
6. Explain the principle of the "flaming arc" lamp. What causes the high efficiency?
7. Explain the principle of the "mercury vapor" lamp.

ILLUMINATION

PHOTOMETRY

A photometer is a light measurer. It is usually an instrument for measuring the intensity of a source or the intensity of the illumination resulting therefrom. Various standards have been employed as a basis for comparison. The **candle power** is the usual standard of intensity of a **light source.** The British standard candle was based upon a flame which burned 120 grams of spermaceti wax per hour from a candle ⅞ of an inch in diameter. In Germany a paraffin candle was employed as a standard, the unit being called the **Hefner.** The latest determination by the Reischenstaldt gives a value of 9 for the Hefner as against 10 for the standard candle. That is, the Hefner is equal to 0.9 of a standard candle.

Great difficulty is experienced in comparing sources of light because the sources do not contain equal percentages of luminous rays. The luminous rays in various lamps are approximately as follows:

Kerosene oil lamp	3%
Gas lamp	4
Incandescent carbon lamp	5
Tungsten vacuum incandescent	12
Tungsten gas-filled lamp	30
The sun	34
Flaming arc	70
Fire-fly	100

The "candle power" as its name indicates is the unit of intensity of a source of light as compared with a standard candle. Strictly speaking it expresses intensity on one direction only. The candle power of a lamp is usually different in every direction. The **average** or **mean** candle power expresses the average of the intensities in a great many different directions. For example, the mean lower hemispherical candle power of a lamp is the average of the candle power values in all directions below a horizontal line drawn through the center of the source of light. The mean spherical candle power of a lamp is the average in all directions. When an incandescent lamp is spoken of as giving

so many candle power, the average of candle power values in all horizontal directions is usually meant. That is, the mean horizontal candle power.

The **foot-candle** is the unit of intensity of **illumination.** That is, the illumination obtained on a surface one foot away from a light source of one candle power, when the surface is at right angles to the light ray.

The **lumen** is the unit of quantity or **flux of light.** This is a very useful unit with which to work. One lumen of light is the quantity necessary to produce one foot candle average intensity of illumination over an area of one square foot. Reference to Fig. 1265 will show what is meant by quantity or flux of light.

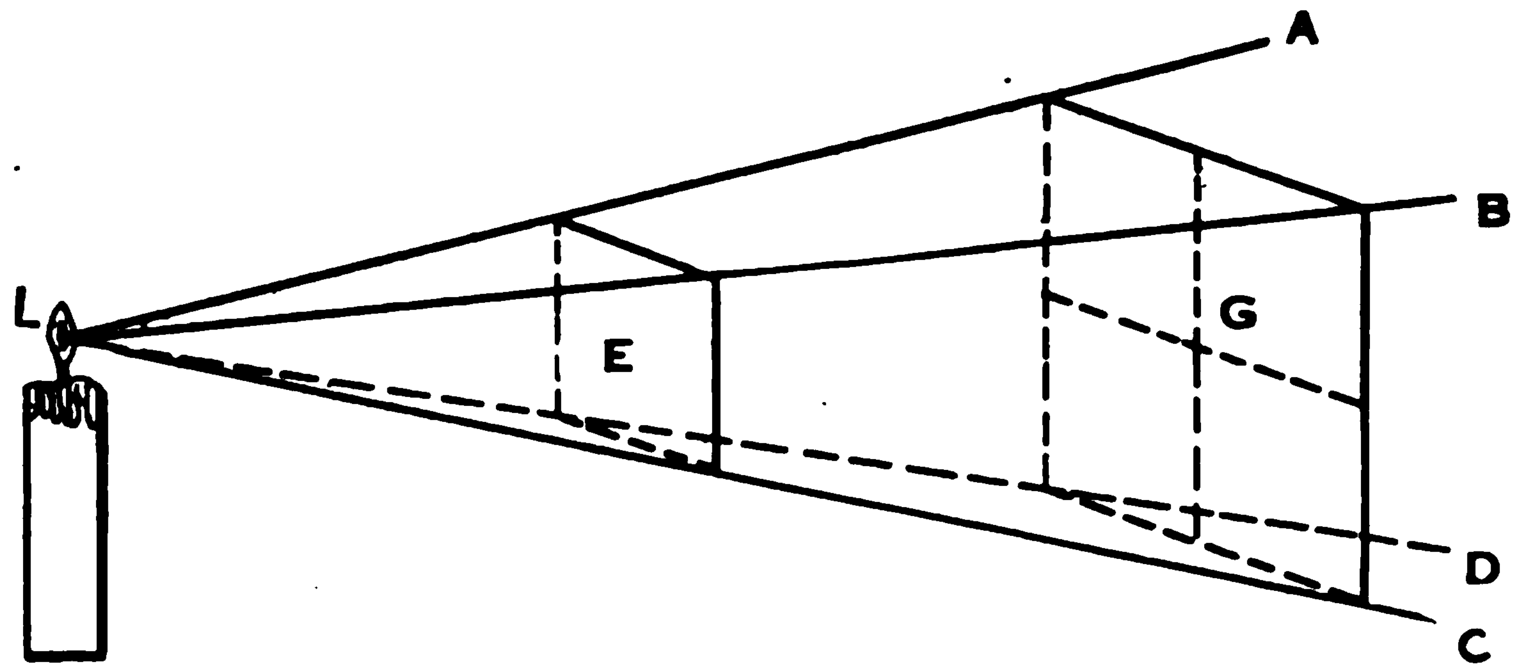

FIG. 1265.—Illustrating the "law of the inverse square."

The solid angle included by the lines *L-A*, *L-B*, *L-C*, *L-D*, may be considered as including a certain quantity of light. The intensity or candle power may be different for every position within the solid angle. That is, *L-A* may be of one candle power, and *L-B* one and a half candle power. But with all of these different intensities or candle powers the quantity of light within the angle may be considered as definitely fixed. Suppose this quantity is one lumen. Suppose the area of the surface *E* is one square foot. Then the average intensity of illumination on *E* is one foot candle, since the definition of a lumen is the quantity of light which will give one foot candle over an area of one square foot. The intensity of illumination at some point on *E* may be two foot candles, at another point it may be one-half foot candle, but the **average** intensity must be one foot candle. Now suppose the lumen of light strikes the surface *G*. Assume that *G* is twice as far from the light source as *E*. The area of *G* will then

be four times the area of E or four square feet. The average illumination on G is therefore one-fourth of a foot candle, since one lumen spread over four square feet will give an average illumination of one-fourth of a foot candle. This also shows graphically why it is that the foot candle intensity of illumination varies inversely as the square of the distance from the source.

Lamps are now quite frequently rated in lumens instead of candle power. Roughly, the lumens are equal to ten times the candle power. Accurately the lumens are equal to 12.57 times the candle power. That is to say, as there are 12.57 square feet on the surface of a sphere of one foot radius, the total flux of light emanating from a source of one candle power would be 12.57 lumens, and the illumination on each square foot of the surface of such a sphere would be one candle foot.

It is easy to lay out lighting systems figuring with light in lumens. Suppose there is a room 10 feet square and 10 feet high with a 100-watt Mazda gas-filled lamp and reflector at the center of the ceiling. This lamp gives approximately 1,000 lumens of light. Suppose the reflector and walls and ceiling absorb 60% of the light. The efficiency under which the light is utilized is then 40%. The useful lumens actually producing illumination are therefore 40% of 1,000 or 400 lumens. The area of the floor of the room being 100 square feet there will be an average of four lumens to each square foot while the average intensity of illumination on the floor is about one foot-candle.

It is customary in practice to work this problem backward, starting with the desired illumination in foot candles. The number of lumens desired to light the room is then found and finally the number and size of the lamps necessary.

The lumens produced by the different lamps varies with their size and make. Small Mazda lamps give about 12½ lumens per spherical candle power. Type C gas-filled Mazda gives as high as 18 lumens per spherical candle power.

Photometers

Light is a vibration of ether waves. The length of a wave of sun light is approximately $\frac{1}{50000}$ of an inch long. White light is made up of seven primary colors. The longest wave is red and the shortest violet. The ultra violet rays are not visible. As the eye must be the judge in each case, in order to measure the

intensity of light beams, the various sources must be compared before the eye. Every light ray contains in addition to the luminous rays, thermal rays which produce heat and actinic or chemical rays which are active in affecting a photographic plate. Light is measured in candle power by means of a photometer.

The Shadow Photometer.—One of the earliest of these instruments is the **Rumford shadow photometer** shown in Fig. 1266.

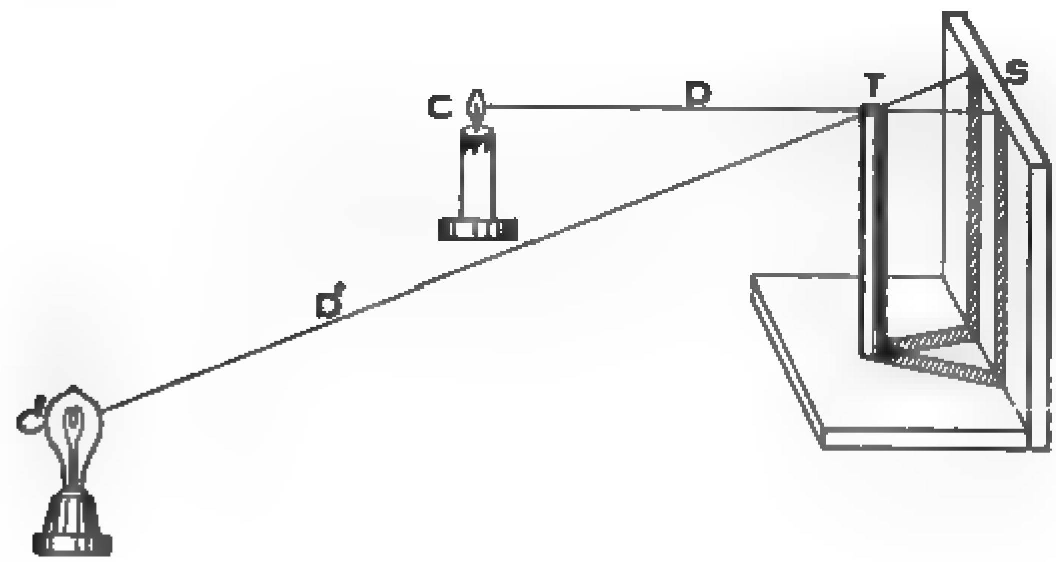

FIG. 1266.—"Rumford" shadow photometer.

Here a standard candle is placed at C. At another point a lamp C', whose candle power is to be compared, is placed at a greater or less distance and at an angle with respect to the fixed source. These two sources each throw a shadow of the rod, T, upon the screen S. By moving the standard lamp nearer or

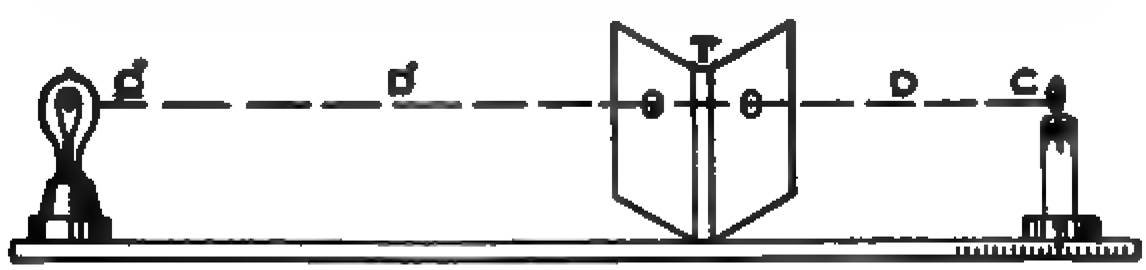

FIG. 1267.—"Bunsen" grease-spot photometer.

farther away the intensity of the two shadows may be brought to the same value When the shadows are equal in intensity the candle powers of the two sources are to each other directly as the square of their respective distances from the screen Thus

$$C : C' :: D^2 : D'^2.$$

The Grease Spot Photometer.—An improvement upon this crude device is shown in Fig. 1267. This pictures the **Bunsen**

grease spot photometer. If a sheet of paper has a grease spot in the center and is held up to the light, the spot will appear lighter or darker than the surrounding paper depending upon whether the intensity of the light on one side is greater or less than on the other. Whenever light strikes an object the result is three fold. It may be reflected back from the surface, transmitted through the surface, or absorbed by the surface. A piece of translucent paper does all three of these things. The light that is reflected produces no effect upon it. The light that is transmitted illuminates beyond it, while the rays that are absorbed, heat the paper. When a light beam strikes a paper surface in the center of which is a grease spot, part of the light passes through the grease spot

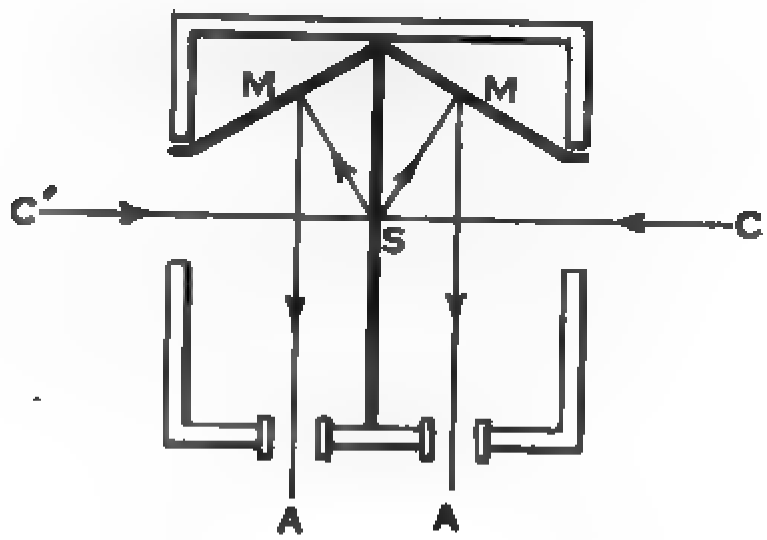

FIG. 1268.—Sectional view of "sight box" for "Bunsen" grease-spot photometer.

making the spot darker on the side from which it is transmitted than the surrounding space from which it is reflected. On the other side of the sheet, however, where the illumination is less, the light transmitted through the grease spot causes it to be brighter than the surrounding space when so illuminated.

When both sides of the paper are illuminated to equal intensities the grease spot disappears. This is the principle involved in obtaining a balance between two light sources in the Bunsen grease spot photometer. In the sight box for this photometer shown in Fig. 1268, there are two mirrors, *M-M*, which are simultaneously viewed by a person's two eyes through openings *A-A*. The mirrors are placed at such an angle as to reflect to the eye simultaneously both sides of the translucent screen *S*, containing a grease spot in the center. The two sources of light

send their rays into the box on the two sides, C and C'. The screen of this sight box is placed at T, Fig. 1267, and is moved back and forth between the standard source C and the lamp under test at C'.

By varying the relative distances D-D', a balance may be obtained. When the grease spot disappears or is illuminated to an equal intensity on both sides the candle power of the unknown lamp may be obtained from the same formula as above:

$$C : C' :: D^2 : D'^2.$$

The Lummer-Brodhun Photometer.—A more accurate form of photometer is the Lummer-Brodhun instrument. The

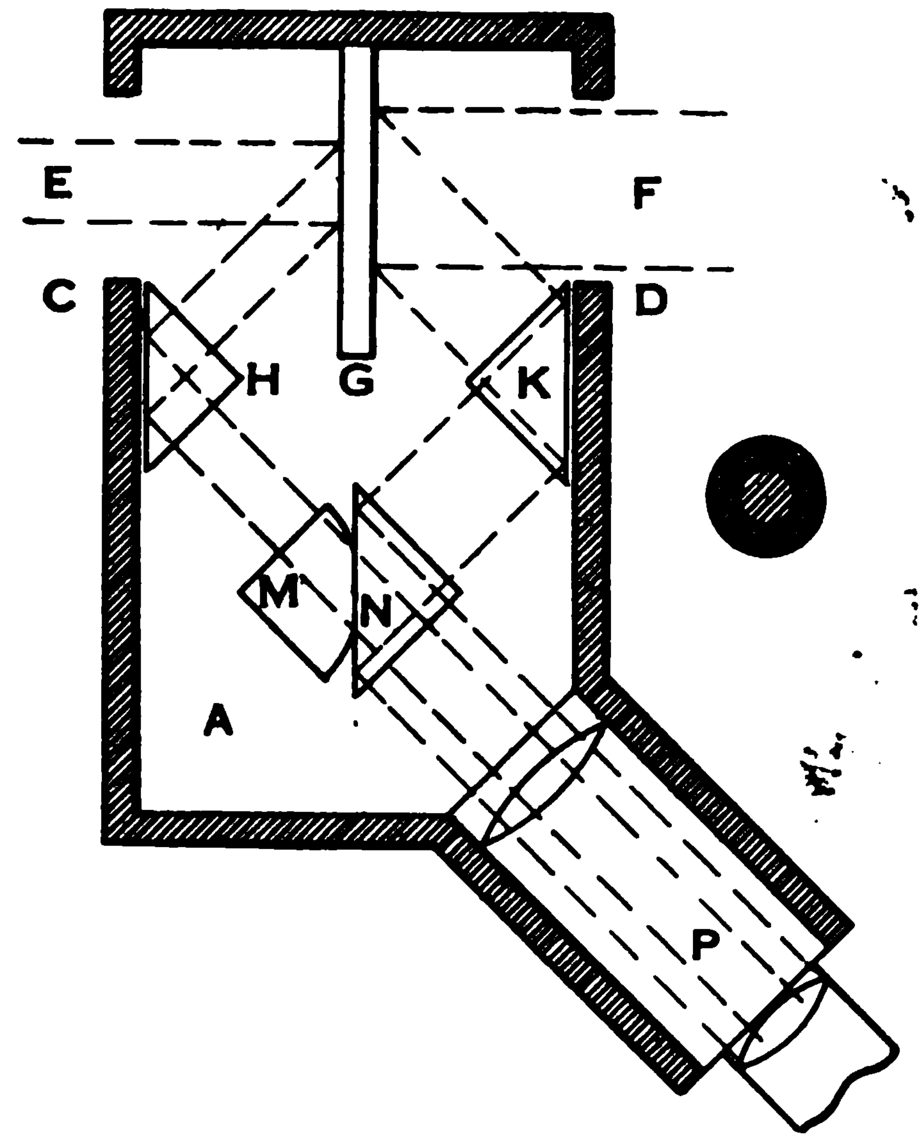

FIG. 1269.—Sectional view of "sight box" for Lummer-Brodhun photometer.

arrangement of the scale is the same as in Fig. 1267 but the sight box is radically different and is shown in Fig. 1269. It consists of a metal box, A, with openings at C and D through which beams of light E and F pass from the two sources to be compared, and fall upon the white surface of a screen of magnesia G. This surface must be kept scrupulously clean and the light will then be very well diffused and will cause definite proportions to be reflected upon the right angled glass prisms H and K. When a

beam of light falls at right angles upon one of the shorter faces of such a prism it will be totally reflected from the sides which form the hypotenuse of the triangle and as the angle which the reflected rays make with the reflecting surface is the same as the angle which the incident rays make with that surface, it follows that the reflected rays will emerge from the prisms at right angles with the face Hence portions of the beams E and F pass through the prisms H and K respectively and strike on two more right angled prisms M and N. One of these prisms has a portion of its hypotenuse face removed by a sand blast, leaving only a circular piece undisturbed The prisms M-N are placed together so that the smooth face on M is in optical contact with N so that at that particular spot the

FIG. 1270 Exterior appearance of foot candle meter, built by the General Electric Company.

two prisms act optically as a cube and rays of light coming from the prism H pass through M and N and enter the telescope P. Rays from the prism K which impinge upon the prism N pass through M where they fall upon the central spot, but where they strike upon the other portions of M they are totally reflected. The observer looking through the telescope sees therefore a circular disc of light due to E surrounded by a circle due to F The disc is darker or lighter than the ring, according to the relative illumination of the two surfaces on the screen G Assuming F to be the stronger beam the sight box is moved away from that source until the line of demarcation between the ring and

the disc disappears, which will indicate that the intensity of the two illuminations are then equal and the preceding formula to determine the candle power of the unknown lamp in comparison with the known lamp may be employed.

Foot-Candle Meter

For ascertaining the intensity of illumination at any point it is more important to know the candle-feet on a particular surface than the candle power of the source. For this purpose a very simple foot-candle meter has been devised by The National Lamp

Fig 1271 —Details of "sight box" of foot-candle meter

Works, of Cleveland, Ohio. This instrument, Fig. 1270, is a small, compact device which measures the actual illumination and shows at a glance how much light is being supplied at any given point. The principle is similar to that employed in the Bunsen grease-spot photometer. Instead of a sheet of paper with a grease spot at the center, a piece of clear glass is used on which are two thicknesses of paper. One which is fairly opaque, contains a row of round holes The other is highly translucent This

Fig. 1272.—Screen indicating foot-candles.

screen forms one side of a light box which is so constructed that the screen is illuminated from within to a much higher intensity at one end than at the other The exposed side of the screen is very nearly uniformly lighted The round spots appear brighter than the surrounding screen at one end and darker at the other. It is evident that at the point where the spots change from brighter than their background, to darker, the illumination on both sides of the screen is, as with the grease spot photometer, approximately the same When the instrument has once been calibrated the intensity of the illumination on the screen may be

read at a glance Fig 1271 illustrates the arrangement of the light box. Fig. 1272 shows the appearance of the screen when illuminated from without and at the same time from the standard source within. In this figure it is evident that the illumination from without is about ten foot-candles It is, of course, important that after the foot-candle meter has been calibrated the light supplied to the screen from within shall be constant for all readings or the indications will be in error. In the complete outfit, which is shown in Fig 1270, a rheostat is connected in series with the standard lamp and battery. This permits the voltage applied at the lamp to be maintained at a constant value

FIG. 1273 Interior details of foot-candle meter

as the battery gradually depreciates. So long as the voltmeter registers the required voltage on the lamp, the proper illumination on the photometric screen is obtained. The dry batetry is inexpensive and can readily be replaced. The interior arrangement of the instrument, showing voltmeter, lamp, rheostat and light box, is shown in Fig 1273

A suitable intensity of illumination for an industrial plant is about four foot-candles Where fine work is required it may be necessary to raise this to eight foot-candles. School classrooms should be illuminated between these values. Store show windows may require from ten to seventy foot-candles; offices from five to ten and church auditoriums from two to four.

Effect of Colors on Illumination

The color of walls and other surfaces has an important bearing upon the illumination of a room because of the different reflecting powers.

The reflecting powers of various materials is approximately as follows:

Whitewashed wall	82%
White blotting paper	82
Yellow wall paper	40
Blue wall paper	25
Black cloth	1.2
Black velvet	0.4

The problems involved in securing proper illumination include the consideration of:

Efficiency.	Protection of the eye.
Uniformity.	The color values.
Diffusion.	The general appearance.

A good lighting system is one which combines these characteristics in their proper proportions. They are not all of the same importance. Efficiency, for example, is sometimes extremely important and at other times of no importance whatever. In its strict sense efficiency may be defined as the useful percentage of light which actually produces illumination on the working plane, or what remains after subtracting the light absorbed by the reflecting equipment and the ceiling and the walls.

By uniformity is meant the uniformity of illumination. Absolute uniformity is never necessary. Variation of 30% from the mean intensity of illumination is permissible for all practical purposes.

Diffusion is a far more important factor in certain classes of work. This refers to the degree at which light, received at any point, comes from different directions. Thus the diffusion is excellent with indirect lighting where the light on the working plane comes from a large area, the ceiling. An extreme case of lack of diffusion is found where the illumination is obtained from a single opaque reflector. The light then comes from a single direction.

With the increasing use of light sources of high brilliancy, protection of the eye is becoming more and more important.

In a well-designed system the eye will be protected from the necessity of ever looking at a brilliant source of high illumination or an extreme contrast of light and shade.

Color values of light is assuming a great importance. Artificial light should approach as nearly as possible in color that of daylight.

SECTION XXIV CHAPTER III

ILLUMINATION

PHOTOMETRY

1. What are the relative efficiencies of various light sources?
2. Define a "candle power."
3. Define a "candle foot."
4. Define a "lumen."
5. Explain the principle and operation of the Rumford shadow photometer.
6. Explain the principle and operation of the Bunsen grease spot photometer.
7. Explain the principle and operation of the Lummer-Brodhun photometer.
8. Explain the principle of the General Electric foot-candle meter.
9. What are the relative reflecting powers of different colored walls?

SECTION XXV CHAPTER I

PRODUCTION AND UTILIZATION OF ELECTRICAL POWER

SOURCES OF POWER

There are two great natural sources of energy upon which our modern civilization may draw in developing electrical energy: coal, including oil and natural gas, and water power.

It is interesting to consider the coal mined in the United States during the past century. The figures are as follows:

	Tons
In 1825	100,000
1836	1,000,000
1852	10,000,000
1882	100,000,000
1920	1,000,000,000
1958 (estimated)	10,000,000,000

Dr. Steinmetz states that the chemical energy of 1 ton of coal equals approximately the electrical energy of 1 kilowatt-year.

In 1918, the consumption of coal in this country was approximately 867,000,000 tons, which had the electrical equivalent of 867,000,000 kilowatt-years. Inasmuch, however, as the average efficiency of conversion of the chemical energy of fuel into electrical energy is probably only 10%, the coal production, converted into electrical energy, would give about 87,000,000 kilowatt-years. Assuming that only one-half of the coal is used for power, at an efficiency not exceeding 10%, the other half being used as fuel for metallurgical work, and for various other purposes, at an average efficiency of 40%, we find that only about 217,000,000 kilowatts is available continuously throughout the year as a result of the production of 867,000,000 tons of coal.

The development of water power in the country at the present time is limited by economical considerations to the use of only the largest and most concentrated powers. The total value of the hydraulic energy of the United States, each year, based on rainfall from the elevation where it fell, down to sea level, is approximately 1,000,000,000 kilowatt-years, but this great volume of energy is not available, as much of it cannot be utilized and much is required by agriculture. Making all allowances for loss of efficiency

in development and a minimum allowance for agriculture, gives, according to Steinmetz, about 230,000,000 kilowatt-years as the maximum possible hydro-electric power which could be produced if every river, stream, brook and creek, throughout its entire length from the spring to the ocean, during all seasons, could be used.

It is surprising to note that the maximum possible hydraulic energy of 230,000,000 kilowatts is only a little more than the total energy produced in 1918 from coal. This means that the hope that when once the supply of coal begins to fail we may fall back upon the water powers of the country for our energy is an idle dream, because if it were possible to utilize the entire potential energy of the water powers of our country, and every rain drop were used, it would not supply our present energy demand.

There is no question but that hydraulic energy should be developed as rapidly as practicable, in order to supplement the energy derived from coal, but it can never replace it as a source of energy.

There are three general classes of water power to be found in this country:

First, those derived from the swift rivers in New England, where the water flows through a rocky and hilly country, and the streams are swift and powerful with frequent rapids and cascades.

Second, that class of water power derived from slow streams that flow through a flat country, such as the Mississippi Valley.

Third, there are many fine water powers that come from mountain streams, fed from small springs and the melting of winter snows. The available heads in such localities are often enormous, reaching in some instances 1,000 feet or more in height, and, although the volume of water may seem absurdly small, it is possible, as in the Fresno, California plant, to develop 140 mechanical horse power for each cubic foot per second passing the wheel.

From another angle, hydro-electric power may be classified as follows:

First, plants depending on a uniform stream flow. The Niagara and St. Lawrence rivers belong to this class.

Second, plants on rivers having a variable stream flow. The Susquehanna belongs to this class.

Third, plants located on streams regulated by storage reservoirs. The Connecticut, Hudson, Delaware and Potomac rivers belong to this class.

The small heads of from 20 to 40 feet available from upland New England rivers do not yield power enough to serve anything but trivial purposes, unless the stream has considerable volume. With such heads only 2 or 3 horse power per cubic foot per second can be obtained. Nevertheless, such rivers furnish the great bulk of water power now utilized, although subject to considerable disturbance in the way of freshets.

Lowland streams can rarely be developed to give more than 10 or 15 feet of head and therefore demand an immense volume to produce any considerable power. This is illustrated in the great plant at Keokuk, Iowa, on the Mississippi.

When the natural conditions are such as to permit storage of water in reservoirs under high heads, irregularities in supply can frequently be very satisfactorily smoothed out. Now it happens that at 650 feet effective head, one mechanical horse power can be produced with almost exactly one cubic foot of water per minute, at 80% efficiency in the wheel. A 500-h.p. plant can therefore be maintained with a water supply of 30,000 cubic feet per hour. It is possible to store 43,560 cubic feet of water per acre, per foot of depth, so that a single acre, 10 feet deep, will store enough water to operate a 500-h.p. plant at full load for fourteen and a half hours, or, under ordinary conditions of load, for a full day. If the stream supplying the reservoir fell to as low as 15,000 cubic feet per hour in time of drought, the acre of storage would carry the station two days, and 15 acres of storage would carry the plant for a month.

The most serious question involved in hydraulic developments is that of variable water supply. When the supply is low, the output of a plant may be increased by storing the water, or a plant may be installed to utilize what water is available for the most of the year, and its operation may be curtailed through the period of low water. Finally, a steam plant may be installed as an auxiliary to help out the hydraulic plant when there is a shortage of water.

If the head is high, storage is always worth undertaking if the lay of the land is favorable. This involves the construction of a dam, but it may not necessarily be high or costly.

The character of the river bed, topography of the country and local conditions generally, enter into the determination of the proper shape of the dam for storing water. Practically all modern

dams are of concrete construction. Fig. 1274 illustrates a sectional view of a concrete dam built at Lake Spaulding, one of the largest storage reservoirs on the system of the Pacific Gas and Electric Company. At the time of its construction in 1915 it was the highest dam above the river bed in the world, its ultimate height being 305 feet. Its width at the bottom was 185 feet with

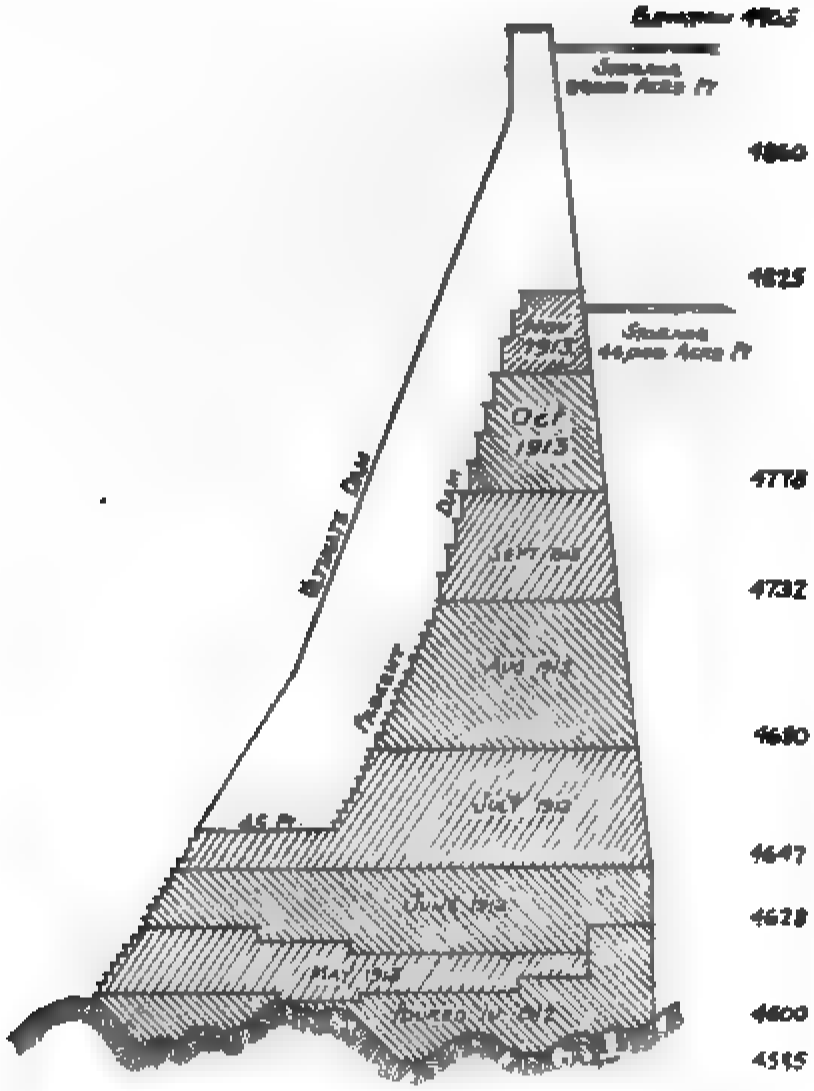

FIG 1274. Sectional view of concrete arch dam of the variable radius type in the valley of the South Fork of the Yuba River near Smart, California, which forms Lake Spaulding, the largest reservoir of the Pacific Gas and Electric system.

a crest 14 feet thick. When first put into operation the dam was raised to an elevation of only 225 feet. As is common with many such hydraulic developments, the dam is curved on the upstream side, thus giving the advantage of an arch between the adjacent hills, which makes it almost impossible to break.

If the cost of impounding the water is such that the sinking fund and interest at 8% does not exceed $32 per horse power, per year stored, it is generally worth while to store it, provided the power can be sold at a fair price. When transmitted power can be had

cheaply, it is worth while for a power user, who is paying say $100 per horse power per year for steam power, to take hydraulic electric power at $50 per horse-power year, for nine months, and to use steam the other three months. To count upon auxiliary steam power, however, for eking out a water supply is not generally applicable, but sometimes proves advantageous.

Steam power on the basis of a twelve-hour day, at a constant full-load output, varies in cost to produce, according to the size and type of plant, the price of fuel, labor, etc., from a little under $20 to a maximum of $125, or even more, per horse-power year. If the load is of a variable character, these figures may be increased from one-third to one-half. Fully developed water powers rent at from $5 to $50, or more, per horse-power year, and may cost, to develop, anywhere from $20 to $150 per horse power. If water power can be developed at not to exceed $20 per horse power, it is cheaper than steam under any consideration, but at $150 per horse power as a development charge, water power is higher than steam, unless the fuel cost is excessively high.

It may be stated on general principles that **if the cost of hydraulic development can be kept below $100.00 per horse power, electrical energy therefrom can be delivered at a cost which will nearly always drive steam power out of business.**

Location of Plant

In planning a power station the first thing to be considered is a proper site. If the plant is to be operated by steam it must be situated favorably with reference to the supply of coal for fuel and water for condensing purposes. These things are of far greater importance than that the plant shall be located at the center of distribution, which would in many instances bring it in the center of a city. Such a location would involve a high cost for ground, and general inaccessibility, as far as fuel and water supply are concerned. Furthermore, with the high voltages now available for transmission purposes there is nothing to hinder the location of a plant at a point remote from the center of distribution, where water and fuel are convenient and ground may be cheap.

Boilers

The tendency in modern steam plants is to employ water-tube boilers exclusively. Examination of a large number of carefully conducted tests show that from 8 to 13 pounds of water may be

evaporated at 212 degrees Fahrenheit, per pound of coal burned. Ten pounds of water per pound of total fuel may be regarded as reasonably good practice in every day work. With a good design it is found that from 10 to 15 pounds of coal are consumed per square foot of grate surface per hour. In large stations mechanical stokers are invariably employed.

Steam Turbines

The bulky, expensive and cumbersome steam engine has given place in all large modern stations to the steam turbine. The fundamental principle is the same as that involved in the water turbine, namely, directing a fluid under pressure against a series of rotating buckets. In the steam turbine a high rotative speed is necessary for efficient running. Here, as in hydraulic impulse

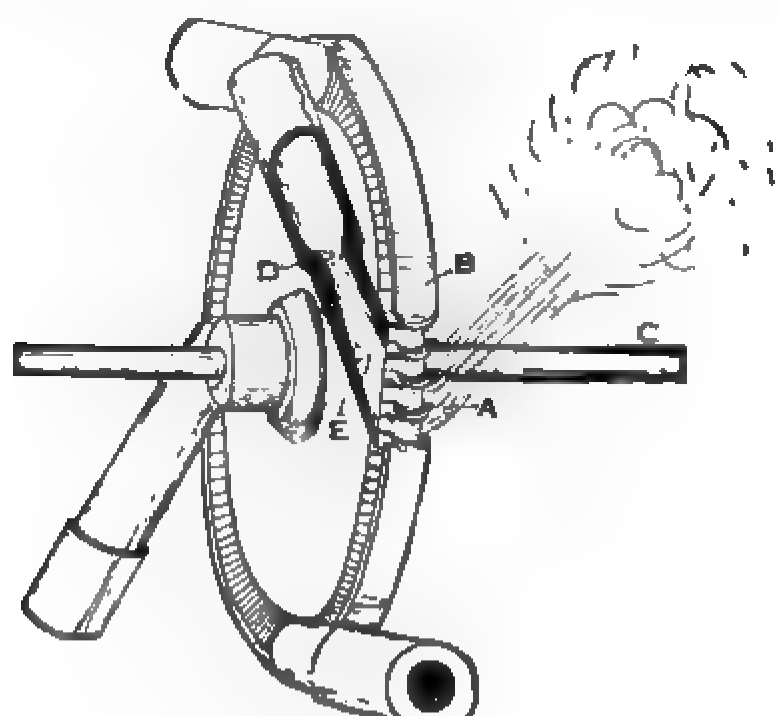

Fig. 1275.—DeLaval impulse-type steam turbine.

wheels, the peripheral velocity should be about one-half the spouting velocity of the fluid.

There are two types of steam turbine resembling in principle the two types of water turbine, namely, the impulse type and the reaction type.

The DeLaval steam turbine very closely resembles the Pelton water wheel. Both are of the impulse type.

The principle of the **DeLaval impulse type** is illustrated in Fig. 1275. Here steam passes through a restricted passage D and emerges at high velocity from a nozzle E. It then strikes a set

of buckets, A, on the circumference of a wheel, finally exhausting on the opposite side from whence it entered and causing it to rotate at a high speed.

The **Parsons** steam turbine is of the **reaction type.** One of the most widely used machines of this type is the Westinghouse-Parsons turbine. In this machine the steam is passed successively through a large number of turbine wheels in a direction parallel to the axis of rotation. The steam expands sharply against the runner blades and gives them a reactive kick as it leaves. The steam velocity is not the full spouting velocity due to the initial head of steam, but merely that corresponding to the difference in

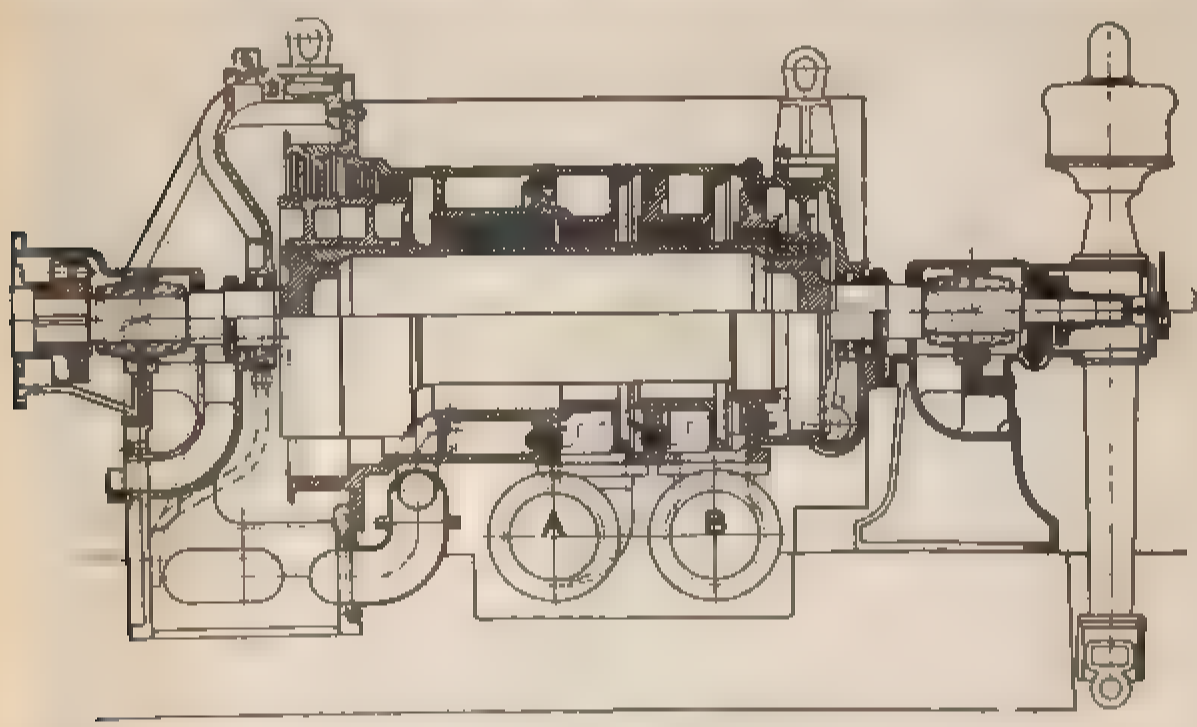

FIG. 1276. Section through high-pressure stage of Westinghouse-Parsons 15,000-kilowatt element of turbo-alternator built for Interboro Rapid Transit Company of New York City.

pressure between one stage and the next. This enables the peripheral speed of the runner to be kept very much lower than in the single stage DeLaval form. Nevertheless, the turbine at best is not a slow-speed machine.

Fig. 1276 is a sectional view of the high-pressure element of a Westinghouse-Parsons steam turbine built for the Interboro Rapid Transit Company of New York City. This portion of the turbine alone develops 15,000 kilowatts and runs at 1,500 r.p.m. The steam, after passing through this unit, goes into a low-pressure section where it gives up the rest of its energy and drives another 15,000-kilowatt unit before passing to the condensers.

The **Curtis** steam turbine is an **impulse machine;** that is, the rotating element is actuated by the impact of steam passing through its buckets at relatively high velocity but without actual expansion in them. The steam is expanded in stationary nozzles, acquiring a relatively high velocity, and then passes through and actuates the moving buckets to another stage without further expansion.

In the reaction type of turbine there are no distinct nozzles; the steam is expanded in both the moving and stationary blades and actuates the former by both impulse and reaction.

Fig 1277 shows diagrammatically the progress of the steam in a Curtis turbine. Entering at A from the steam pipe, it passes

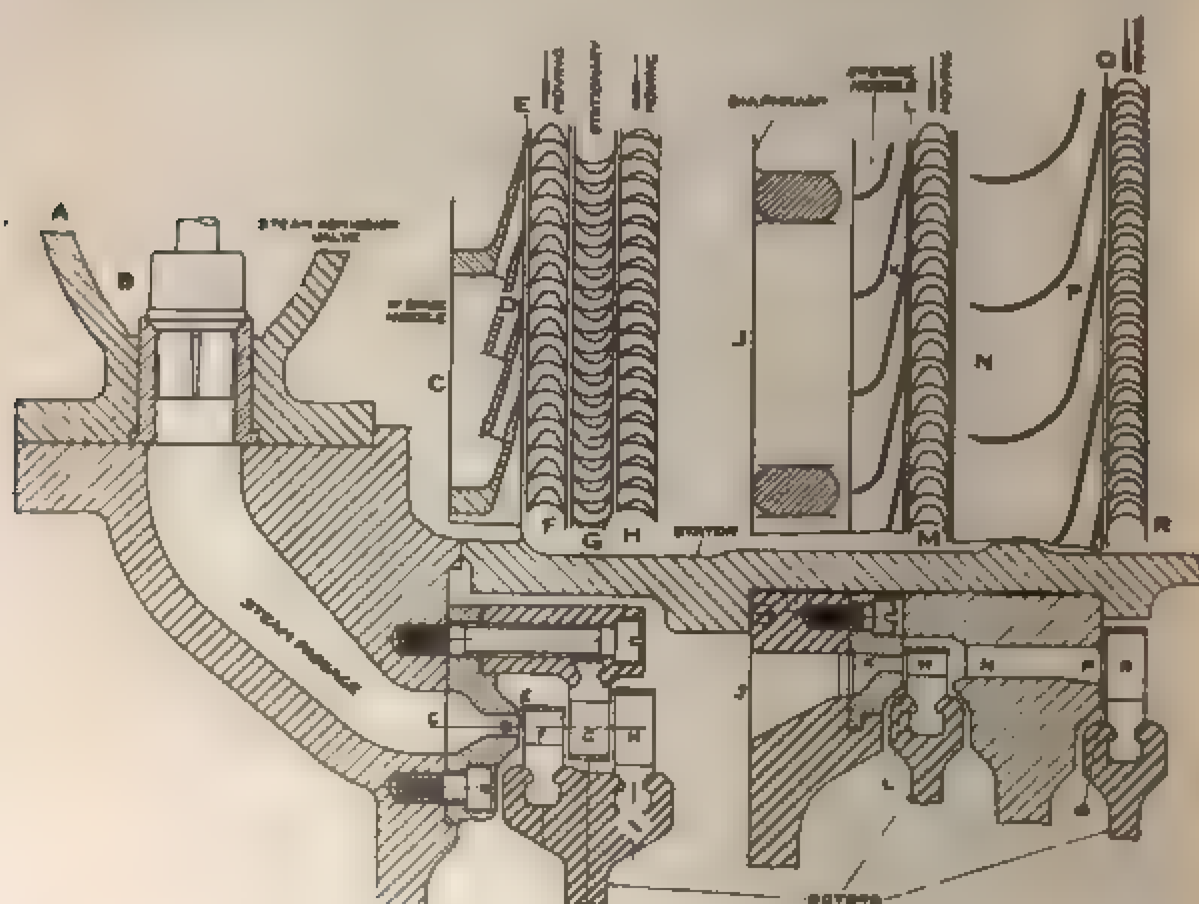

FIG. 1277.—Sectional view of Curtis impulse steam turbine built by General Electric Company.

into the steam chest B, and then through one or more open valves to the bowl C The number of valves used depends on the load and their action is controlled by the governor. From the bowl C the steam expands through divergent nozzles D, entering the first row of revolving buckets of the first stage at E, thence passing through the stationary buckets G which reverse its direction and redirect it against the second revolving row H. This constitutes

the performance of the steam in the first stage or pressure chamber. Another portion of its unexpended energy is abstracted in a second stage from *J* to *R*.

Colfax Steam Plant

An admirable illustration of a proper site is found in one of the greatest steam plants ever designed, that of the Colfax Power Station of the Duquesne Light Company, at Pittsburgh, Pennsylvania.

Fig. 1278 shows the convenient location of this plant with reference to water and coal supply, provision for storage of coal

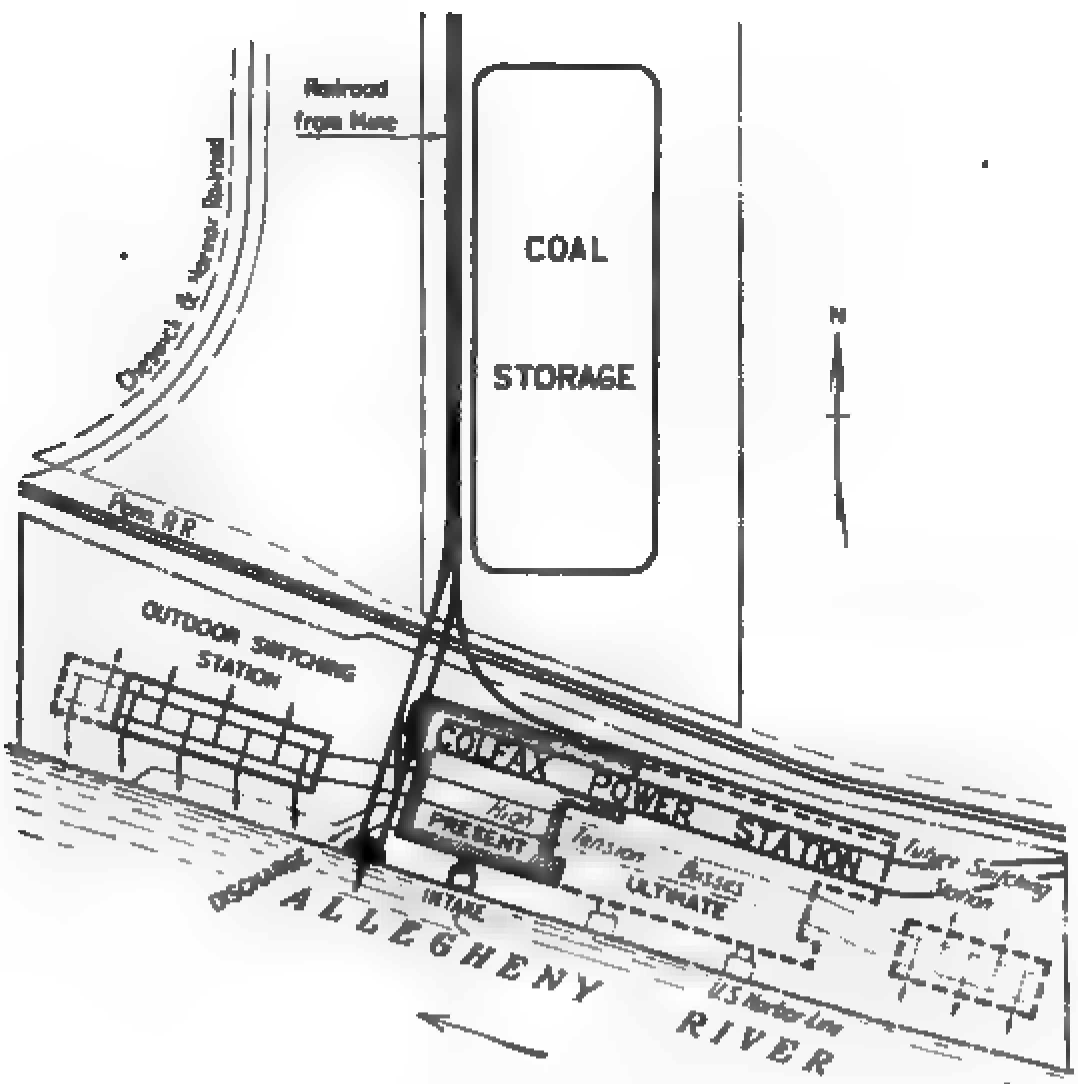

Fig. 1278.—Plan of Colfax station showing location of coal storage, power-house and switching station.

and direction of railroad to mine. At the time of its construction it was one of, if not the largest steam station in the world. It is situated on the Allegheny River, where it is planned to utilize practically the entire water supply of the river for condensing purposes, and immediately adjacent to a coal mine, where fuel

may be obtained for a long time to come, at a minimum cost. The ultimate capacity of this plant is 300,000 kilowatts, derived from turbo-generators. The size of the unit chosen was 60,000 kilowatts, so that the ultimate development may be divided into five or six steps. The station was opened for service on December 18, 1920, with one 60,000-kilowatt turbine and seven boilers.

Fig. 1279 is a sectional view of the latest type of Babcock and Wilcox water tube boilers employed in the Colfax station. These

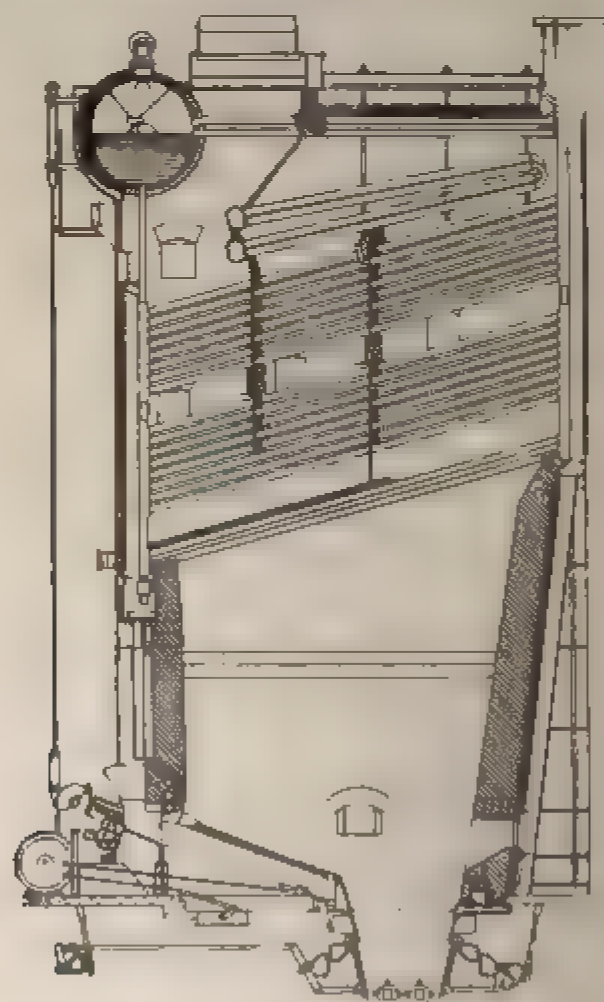

FIG. 1279. Babcock and Wilcox water-tube boilers used in Colfax station of Duquesne Light Company.

boilers are eighteen tubes high with the two lower rows dropped below the tube bank and exposed to the direct heat of the furnace through their whole length. The boilers are exceptionally high so as to give a large furnace volume. The most approved form of mechanical stokers is, of course, employed.

Fig. 1280 shows the plan of the three elements of the 60,000-kilowatt Westinghouse-Parsons turbo-alternators in this station. The high-pressure element is in the center, and the low-pressure elements, one on each side. The three elements are grouped

with parallel shafts, occupying a space 51 feet by 79 feet. Each element is of 20,000 kilowatt capacity. The speed of the high pressure element, is 1,800 r.p.m., and of the low-pressure sections, 1,200 r.p.m. The high-pressure element receives steam at 265

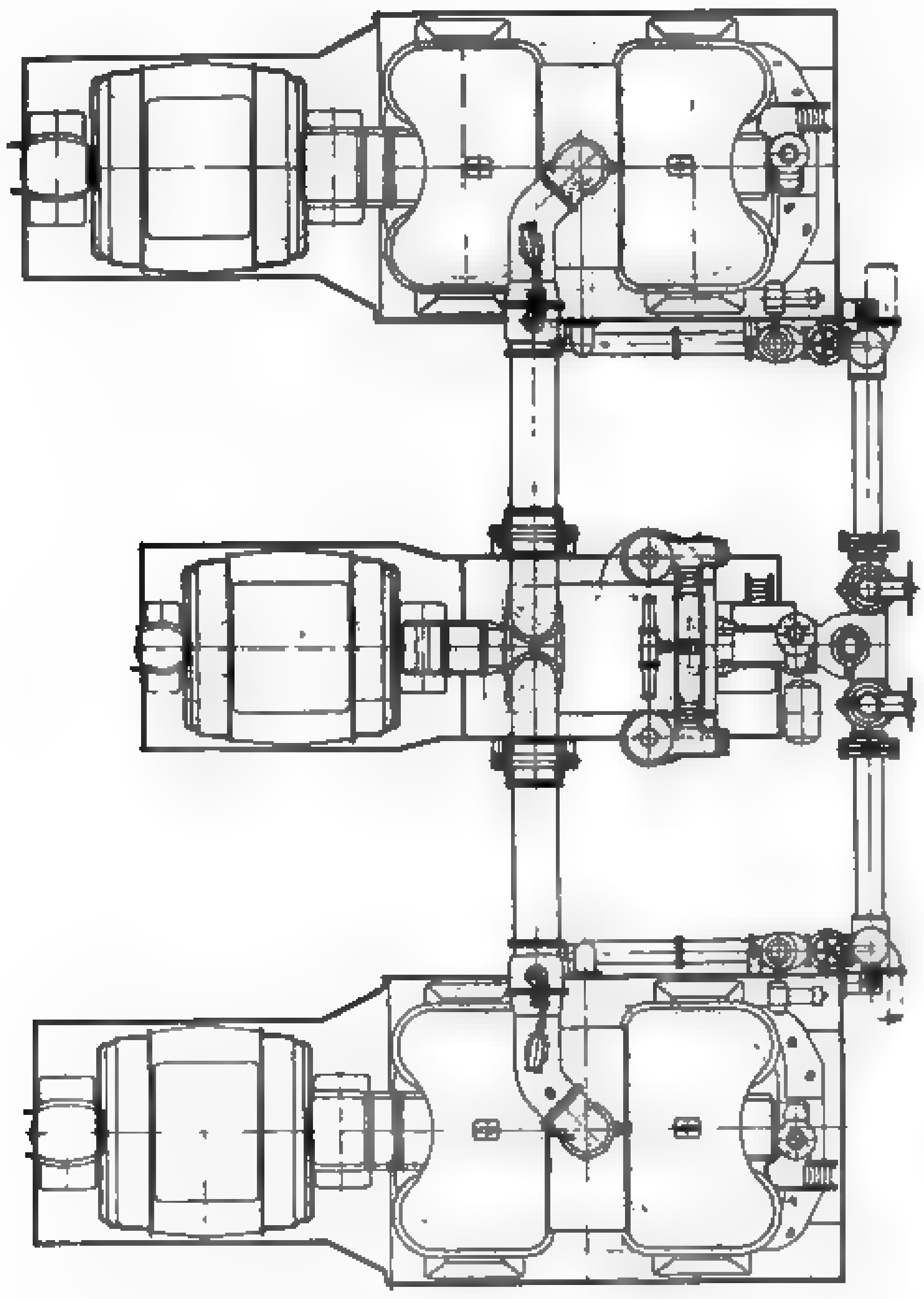

FIG. 1280.—Plan view of 60,000-kilowatt Westinghouse-Parsons steam turbo-generator at Colfax Station of Duquesne Light Company at Pittsburgh.

pounds pressure and delivers it to the two low-pressure elements at 55 pounds. The alternators generate at 12,000 volts, 60 cycles, and supply current to a bank of single-phase transformers of 23,600 k.v.a. capacity each. These are the largest single-phase transformers ever constructed thus far (1921). The windings

are connected in Δ on the low-tension side and in Y on the high-tension side, with a ratio of 12,000 : 66,000 or 12,000 : 132,000 as desired.

Water Turbines

There are two general types of hydraulic turbines, the reaction type and the impulse type.

The modern hydraulic turbine of the reaction type consists of two distinct parts, a system of guide blades and a runner. The runner is the working part of the wheel and consists of a series of curved buckets, so shaped as to receive the water with as little shock as possible and to discharge it only after having utilized practically all of its energy.

The buckets are sometimes arranged so that the water, after having passed through them, leaves the wheel parallel to its axis; sometimes so that the water flows inward and is discharged at the center of the runner; sometimes so that it passes outward and is discharged at the circumference.

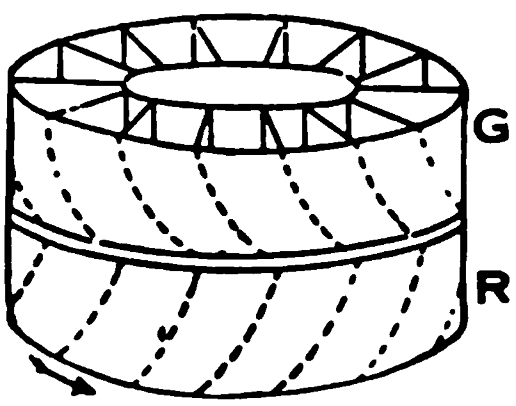

FIG. 1281.—Principle of reaction-type water turbine.

More generally the buckets have a double curvature, so that the water flows along the axis and at the same time either inwardly or outwardly. In most modern turbines of the vertical type, the flow is inward and downward.

Next to the runner the essential feature of the modern turbine is the set of guide blades which surround the runner and which are so curved as to deliver the water to the buckets in such a direction as will enable it to do the most good.

The principle of the reaction type of turbine is well shown in Fig. 1281. Here the water is received through a set of guide blades, the general appearance of which is shown at *G*, from which it discharges against another set of blades carried on the runner *R*. The reaction of the water upon the latter member causes it to rotate in the direction indicated by the arrow.

Fig. 1282 gives a good idea of the construction of a modern **Francis type reaction turbine.** Here the water goes through a scroll chamber, tapering in size and surrounding the turbine proper. A number of guide vanes are mounted upon pivots and so balanced that they can be opened to admit the flow of more or

less water and closed at will. The water enters from the outer circumference and flows radially inward against the revolving vanes, finally discharging vertically downward. The great majority of all vertical shaft water turbines today, for powers up

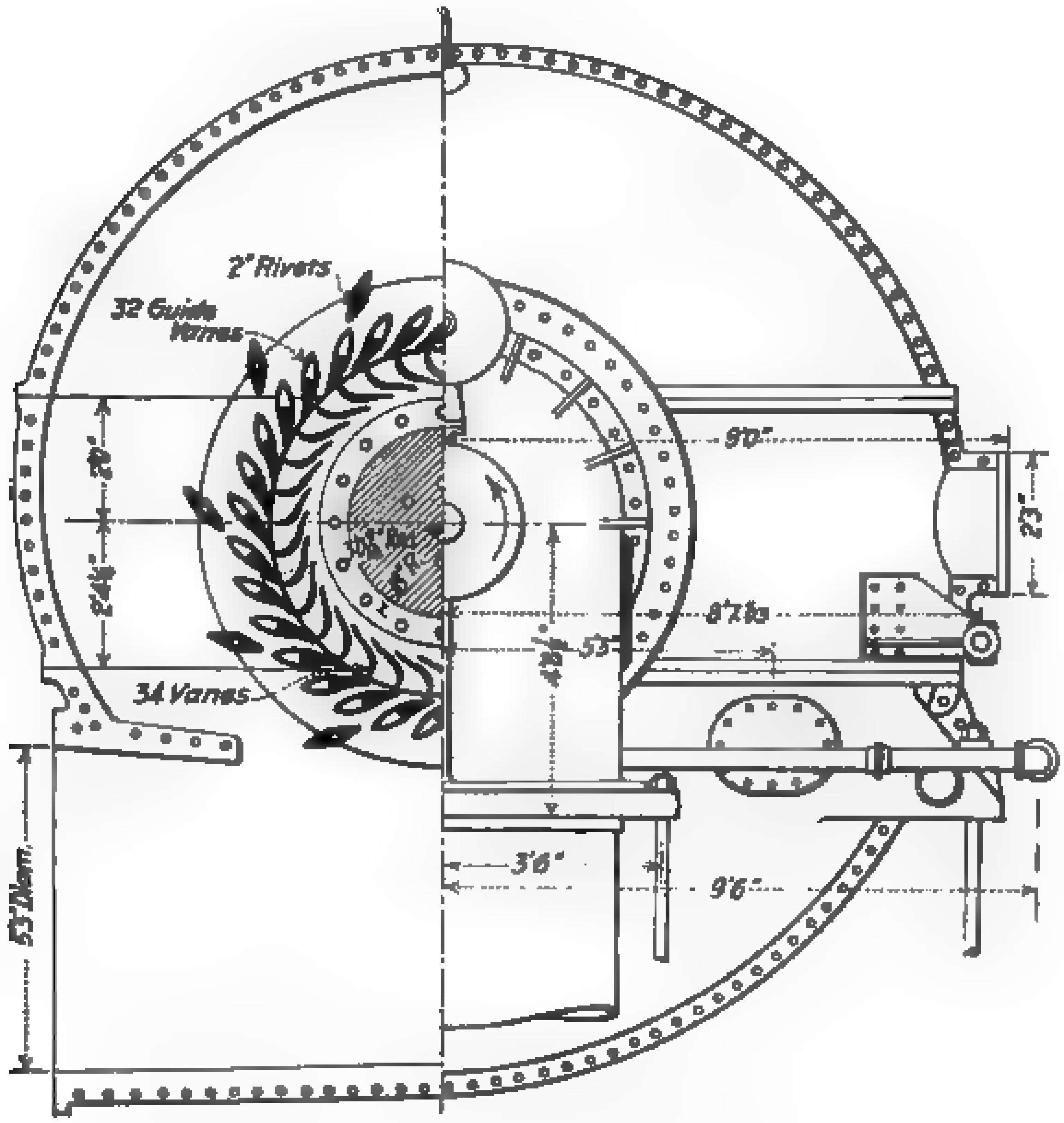

Fig. 1282.—Plan view of Francis type hydraulic reaction turbine.

to and including the 45,000-kilowatt single-runner units at the Queenston Ontario plant, are built upon this plan.

For extremely high heads the **Pelton type** of water wheel is widely used. This machine is of the **impulse type,** and consists of a wheel *E*, Fig. 1283, with a series of buckets, *B*, on the circumference. Against these buckets water is projected from a single nozzle, *A*. Impulse wheels of this type are exceedingly simple and efficient.

For low and moderately high heads the reaction or pressure-type of turbine is almost universally employed. With either type, the

water is admitted from the surface canal or reservoir to steel penstock tubes through head-gates which control the flow These penstocks must be very substantially constructed to withstand the pressure at high heads. They are sealed completely from the top to the turbine, so as to utilize the entire head of water to that point. After the water leaves the pressure turbine it is conveyed to a tail race discharge by means of another airtight steel casing, called a draft tube. The weight of the water column in this tube

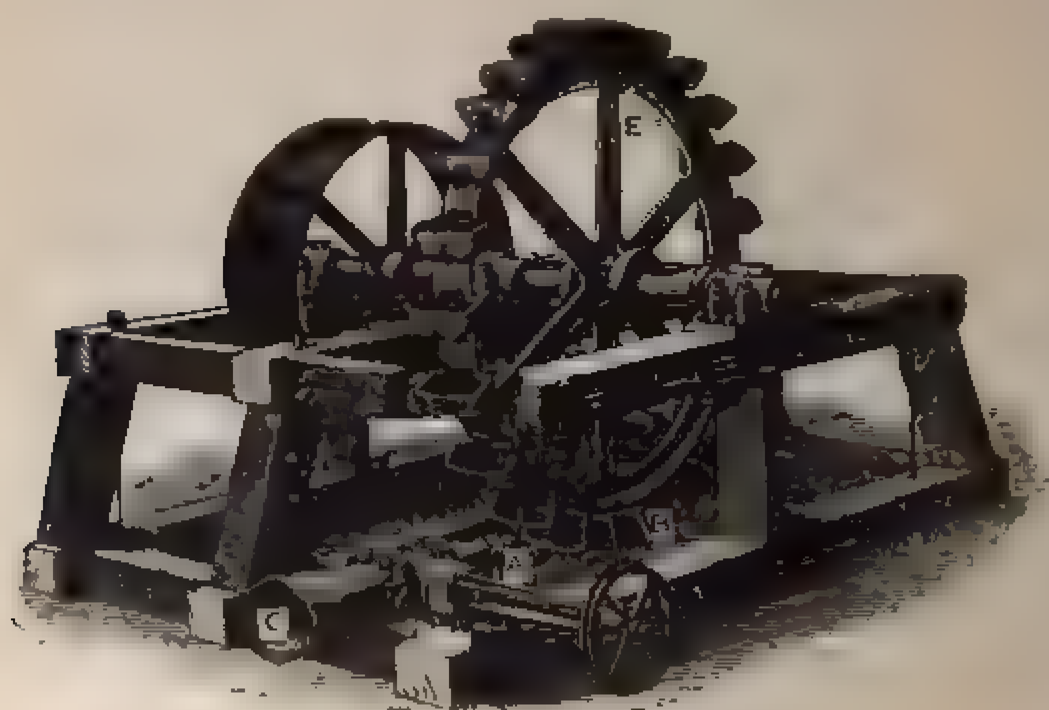

Fig. 1283.—Crude form of Pelton impulse-ty pewater turbine for high heads.

is added to the pressure in the penstock, thereby enabling the total difference in the level of the water between the tail race and the source of supply to be utilized Although a draft tube could theoretically be made 32 feet long, it is found in practice that the water column breaks and a serious water hammer results if the tube is more than about 20 feet in height The most efficient form of draft tube is either curved, or one in which there are baffle plates on the order of the White Hydraucone, or other arrangement to transform the velocity of the water into effective pressure.

Impulse hydraulic turbines and generators are invariably of the horizontal type. Pressure hydraulic turbines and generators are either of the horizontal or vertical type Modern practice in the most recent and largest types of hydraulic pressure turbines is

toward the vertical construction. The "Kingsbury bearing" for taking the thrust of the enormous weight of the revolving member has largely contributed to the success of the vertical type of unit. Briefly, the distinctive feature of this type of bearing is that the stationary part consists of a relatively thin steel plate with a babbitted bearing surface which is supported by a large number of coil springs. The slight flexibility of the plate in conjunction with the spring support permits the plate to conform with any slight irregularity either in the supporting structure or the shaft and thrust collar without causing local unit pressures large enough to prevent the maintenance of a film of oil between the bearing surfaces.

The vertical shaft steam turbines were tried and found unsatisfactory. Practically all modern steam turbines and generators are of the horizontal type.

Queenston-Ontario Hydraulic Plant

If water power is to be the source of energy, the position of the station must be considered in connection with the hydraulic development. The natural site would be near the foot of the working fall, but this may be impracticable in mountainous regions, on account of lack of available space, unsuitable foundation room, inaccessibility or danger of flood. At high heads more latitude is possible in determining the site, since a pipe line may be extended to convenient locations at a moderate cost. At low heads less latitude is permissible, as canal and tail race are relatively costly.

One of the largest developments at this writing is the Queenston-Chippewa plant of the Hydro-Electric Power Commission of Ontario. This development is on the Canadian side of the Niagara River, and is a Government project which will have an ultimate capacity of 650,000 h.p. The general scheme comprises an intake structure branching from the Niagara River at Chippewa. The Welland River was utilized as a part of the supply and was deepened and widened for four and a half miles. A canal was then constructed for a distance of eight and a half miles, from the Welland River to the forebay and gatehouse at the top of the Niagara gorge, about a mile south of the village of Queenston. At the bottom of the cliff, immediately below the forebay, the power house has been constructed.

Fig. 1284 gives a general view of the location of this plant, together with the Niagara and Welland rivers, intake canal, etc.

The first hydraulic development at Niagara Falls utilized an effective head in the case of the power house No. 1 of the American-Niagara Falls Power Company, of only 135 feet. Power house No. 3 of this company, situated just below the International bridge, and known as the Hydraulic Company's plant, increased the effective head to 220 feet. By the plan of the Canadian Hydro-Electric Power Commission, the total available head of

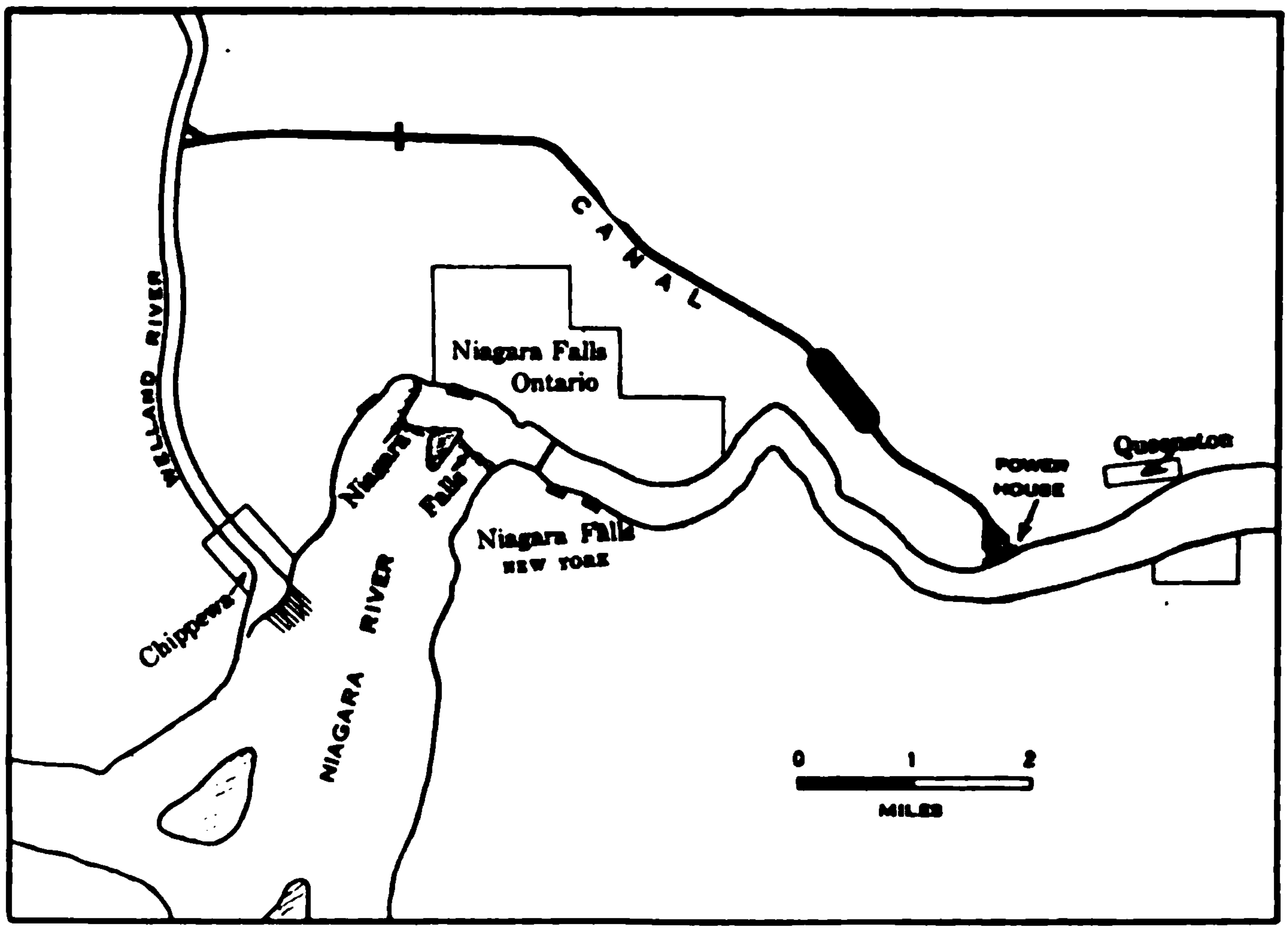

FIG. 1284.—Map showing location of plant of the Ontario Power Commission at Queenston, intake canal, and source of supply from the Niagara River, hrough the Welland River.

Niagara Falls proper, together with the rapids above and below the falls, has been utilized, so that the Queenston plant gets the benefit of an effective drop of 305 feet. The entire design was carried out with the express object of producing power most efficiently from the available water at the lowest possible cost. It is especially noteworthy that this plant contains the largest capacity turbines and the largest vertical shaft generators that have yet been constructed. Each unit is of 45,000 k.v.a. capacity, and there will be five of these units ultimately installed. A single runner turbine drives these units at 187.5 r.p.m. Each turbine is supplied with water from a single steel penstock, double and quadruple riveted, 16 feet in diameter. These penstocks

were designed to sustain a pressure of 12,000 pounds per square inch. The machines generate at 12,000 volts, 3-phase, 25 cycles. The power is stepped up by raising transformers to 110,000 volts, and is transmitted to Toronto, London and Windsor. Each complete generator weighs 1,400,000 pounds and is supplied with a direct-connected exciter, mounted on its top. An auxiliary source of excitation is provided in a motor-generator set for emergency. Two of these generators are now in service, one

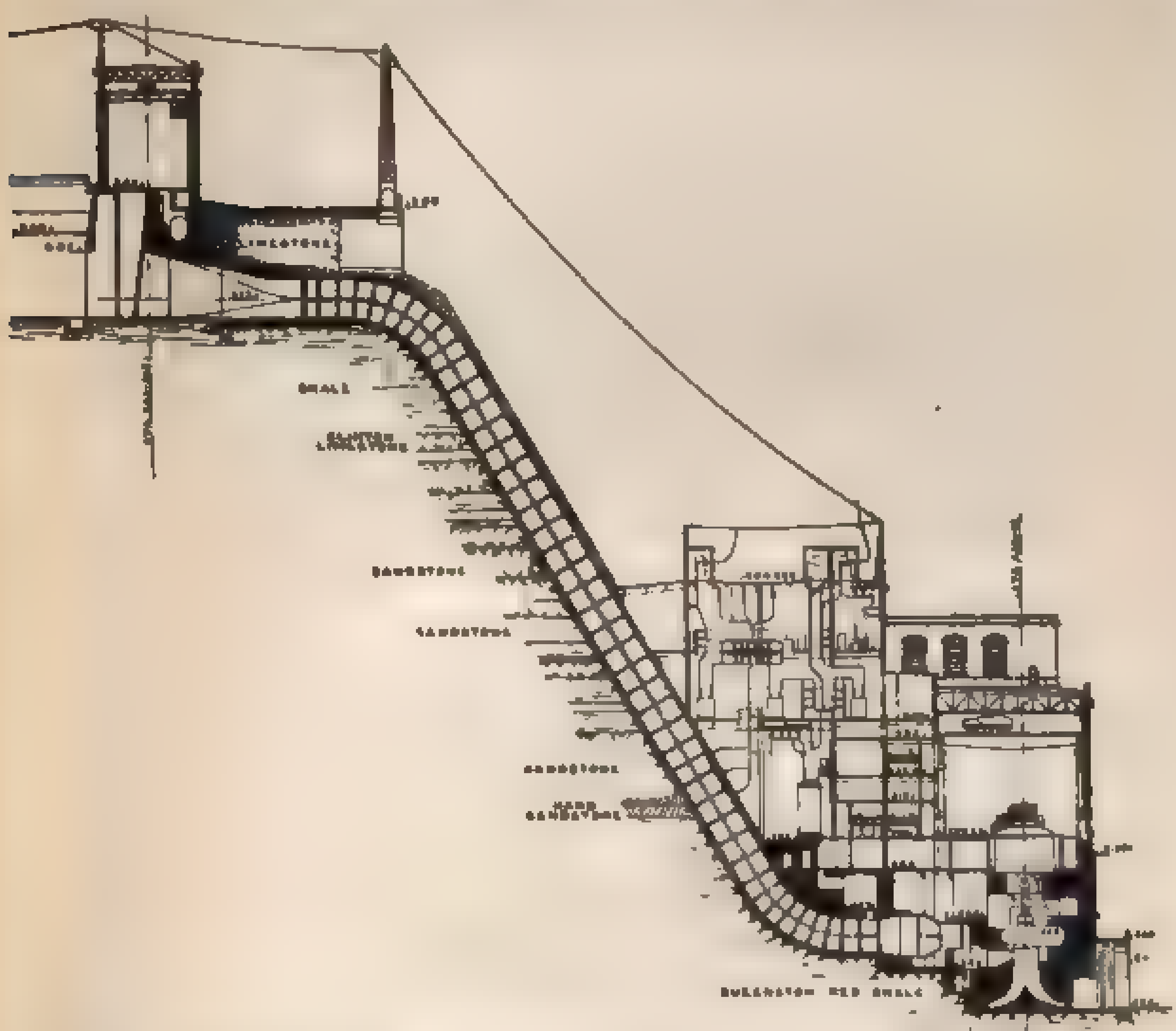

Fig. 1285. Sectional view of gate house, penstock and power house of Queenston plant of the Ontario Power Commission.

built by the Canadian General Electric Company, and one by the Canadian Westinghouse Company.

Fig. 1285 is a sectional view of the forebay, gatehouse, penstock, power house, generator and turbine of this great plant.

Fig. 1286 is a sectional view of these great machines, showing the different floor levels, the scroll chamber for admitting water to the turbine, the system of forced ventilation for cooling, and the details of construction for the generator itself.

Generators

Large generators, when driven by hydraulic turbines, are generally slow speed. The largest units yet constructed are the 45,000-k.v a. units of the Queenston, Ontario, plant running 187.5 r.p.m. These, of course, are multipolar machines with 16 poles in the revolving field.

The large steam-turbine units, such as those in the Colfax Station, consisting of three sections of 20,000 k.v.a. each, are essentially high-speed units, the high-pressure section running

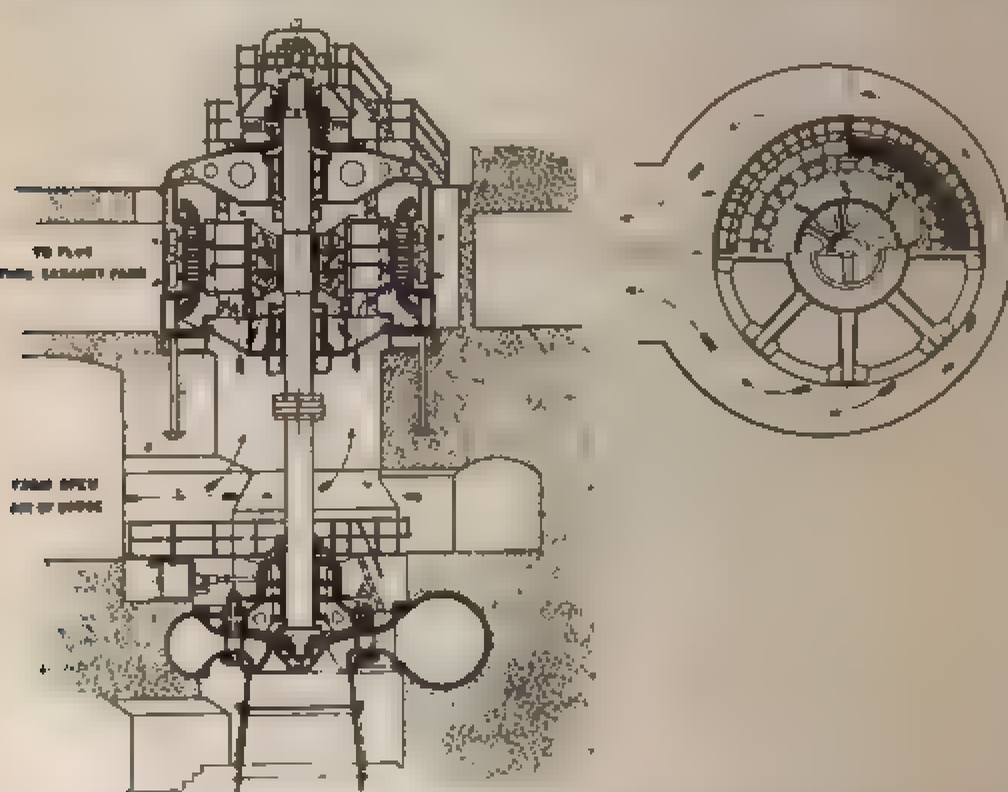

Fig. 1286. -Sectional view of 45,000 k.v.a. Westinghouse generator, single-runner hydraulic turbine, and connecting shaft, illustrating method of ventilating in the Queenston plant of the Ontario Power Commission.

1,800 r.p.m , with only 4 poles in the field and the low-pressure sections 1,200 r p m., with 6 poles in the field Such velocities require extraordinary care in design and careful balancing to insure smoothness in operation.

The tendency in the design of modern large capacity generators is toward the highest practical voltages. At the present time 11,000 to 13,200 volts is the pressure generated The cost of insulation for any higher voltages is out of proportion to any advantage which might be gained, and the size of the copper which it would be necessary to handle if any lower voltage were

employed on large units would render the construction difficult. A pressure of 12,000 volts at the terminals of large alternators is now quite common. These machines are invariably three-phase.

Many years ago a frequency of 25 cycles was adopted for power systems supplying street railways in our large cities. This was chiefly due to the fact that at that time rotary converters could not be built for a higher frequency. In late years the 60-cycle rotary converter has been standardized, with the result that all new installations are being made at 60 cycles, and many of the older stations are being gradually changed over to the higher frequency. A notable example of the persistency of 25 cycles is found in the great Queenston plant, which is being constructed at the lower frequency. The Colfax station is one of the modern 60-cycle plants. An illustration of the tendency to change is found in the Bennings plant of the Potomac Electric Power Company, of Washington, D. C., which is in process of change over from 25 cycles to 60 cycles. The new turbo-alternators now being installed in this plant are of the higher frequency. The 25-cycle current is not adapted for lighting as the pulsations of the current are sufficiently slow to produce an objectionable flicker in the light from standard 40-watt, 110-volt lamps. Wherever 25 cycles is employed it is highly desirable, and in most instances considered absolutely necessary, to install frequency-changers to convert the 25-cycle current into 60-cycle current. These frequency changers are simply synchronous motor-generator sets, differing only in the number of poles on each end. The motor receives current usually at 25 cycles and converts it into 2,300 volts, 60 cycles. From an economic standpoint, it is considered good engineering by many of the larger companies to gradually replace all 25-cycle generating equipment, whether driven by steam or hydraulic turbines, with 60-cycle apparatus, for the sake of eliminating frequency changers, thus enabling all apparatus connected to the system to be of one frequency.

Exciters.—The tendency in modern generating stations is toward the utmost simplicity in design. Alternators are excited with 125 or 250 volts direct current and the revolving member of all large modern alternators is the field structure. This means that slip rings must be provided through which to supply the direct current to the field winding. Designers differ as to the most desirable method of securing the exciting current. Three general plans have been adopted.

First, exciters are driven by independent hydraulic or steam turbines in sufficient number, and connected through duplicate exciting bus-bar circuits to insure against any possibility of failure of the exciting current, which would mean the shutting down of the station. An illustration of this method of excitation is found in power house No. 1 of the American-Niagara Falls Power Company, where five such units will be found, driven by vertical shaft turbines.

Second, a separate motor-generator set is provided, closely adjacent to each generator, for excitation purposes. The motor ends of these sets are supplied with alternating current from a separate alternating current generator, driven by a separate hydraulic wheel. The motors are of the induction type. An illustration of this method of excitation is found in the Keokuk plant on the Mississippi.

Third, the exciter is directly connected to the end of the alternator shaft. If the alternator is of the vertical type, the exciter is carried on top. An illustration of this method is found in the Queenston, Ontario, plant. At this plant, however, additional provision is made in the shape of a motor-generator unit to supply excitation in case of failure of any individual exciter. The motor end of this latter set is supplied with current from a special service unit, consisting of an hydraulic turbine and generator, used for supplying power in and about the station. Many stations are provided with a storage battery floating across the exciter bus-bars, which may be used for excitation of the generators in case of failure of the exciter circuits.

Switching

Current is led from the alternators to switches mounted in iron cases, filled with oil, and designed to successfully interrupt the maximum current which the machines will deliver at any time under normal conditions. These switches are remotely controlled from the bench board, which regulates and directs the output of the station. The switches are closed against the action of a powerful spring by either a solenoid, which is the plan adopted by the Westinghouse Company, or by a geared motor, which is the scheme employed by the General Electric Company. The switch is held closed by a latch. When it is desired to open the circuit, this latch is released by a trigger, actuated in either case by a

small independent solenoid controlled from the bench board The control current for operating the switches and other devices of similar character is generally either 125 or 250 volts, direct current, derived from motor-generator sets with a storage battery kept constantly charged and held in reserve for operating the control circuits in the event of the breaking down of the motor-generator sets. The current is led from the circuit breakers to the raising transformers, where it is stepped up from approximately 12,000 volts to anywhere from 66,000 to 220,000 volts, depending upon the distance to be transmitted. Although three-phase composite transformers mounted in a single case have been used to a considerable extent, there is a tendency toward the use of single-phase transformers, because of the fact that in the event of failure of a single transformer, another may be substituted, and the system continue to operate. With that end in view, large stations generally carry a bank of four single-phase transformers. Three of these are connected in circuit and the fourth is held in reserve. In the event of one of the service transformers breaking down, it is removed and the spare transformer put in its place, with a minimum of delay. Because of the enormous size and weight of these units in large stations, each transformer is kept mounted upon a truck and placed upon railroad tracks, so that they can be conveniently moved when necessary. These transformers are usually connected in Δ on the low-tension side and in Y on the high-tension side. In practically all high-voltage transmission systems it is customary to ground the middle point of the Y. This lessens the insulation strain between any one of the three-phase wires and ground.

Most large stations provide low-tension bus-bar systems in duplicate at approximately 12,000 volts, duplicate sets of raising transformers and duplicate high-tension bus-bars at from 66,000 to 220,000 volts. All important transmission systems are also provided with duplicate sets of transmission lines, usually carried on the same towers, but sometimes on independent towers, all with the object of insuring reliability.

In the Queenston, Ontario, plant, each of the gigantic alternators is not only supplied with its own exciter but operates through an independent set of transformers to an independent high-voltage transmission line. At the same time provision is made for transferring any alternator to any transmission circuit.

Lightning Arresters

At the entrance of each station it is usually customary to provide lightning arresters. High-voltage lines have for many years been supplied with aluminum cell arresters. These are generally mounted in independent cases, each containing a sufficient number of aluminum cones to withstand the voltage of the system and connected through a small horn gap with each incoming line wire. This gap is shortened by a mechanically operated switch for a few minutes each day for the purpose of allowing a discharge to take place from the line to the arrester, in order to produce the high-resistance film necessary to the successful operation of the arrester.

The Line

All long-distance large power transmission lines should preferably be built straight-away. In level country this is generally possible, but in mountainous localities it is somewhat difficult. The right-of-way for the transmission line should be purchased outright, if practicable, and a good roadway constructed adjacent thereto, which may be patrolled and along which vehicles carrying necessary repair parts can travel conveniently. If the right-of-way cannot be purchased it should be leased on a long time contract so that no difficulties will be experienced in maintaining service. Rights along public roads are desirable as they afford excellent facilities for inspection and repair. Right-of-way merely for the line to cross private lands with proper facilities for access can generally be cheaply secured. Steel tower construction is generally preferable to wooden pole construction. Transmission lines should always be of bare metal, sometimes of copper but more generally of bare stranded aluminum. Suspension type of insulators, varying from two or three units at 11,000 volts up to as high as eleven units at 220,000 volts, are now quite generally employed. At the higher voltages, guard rings made of metal, 18 to 24 inches in diameter, around the top and bottom insulators, connected to ground and line respectively and, rigidly supported approximately on a level with the lower edge of the insulator, have proved exceptionally advantageous in equalizing the voltage strain along the whole string. At voltages from 150,000 to 250,000 these guard rings have been found absolutely necessary.

Long-distance transmission lines are generally carried on steel towers of various forms with a spacing between towers and height from ground depending upon conditions. The latest form of tower adopted on the great 246-mile transmission lines between Big Creek and Los Angeles, California, is shown in Fig. 1287.

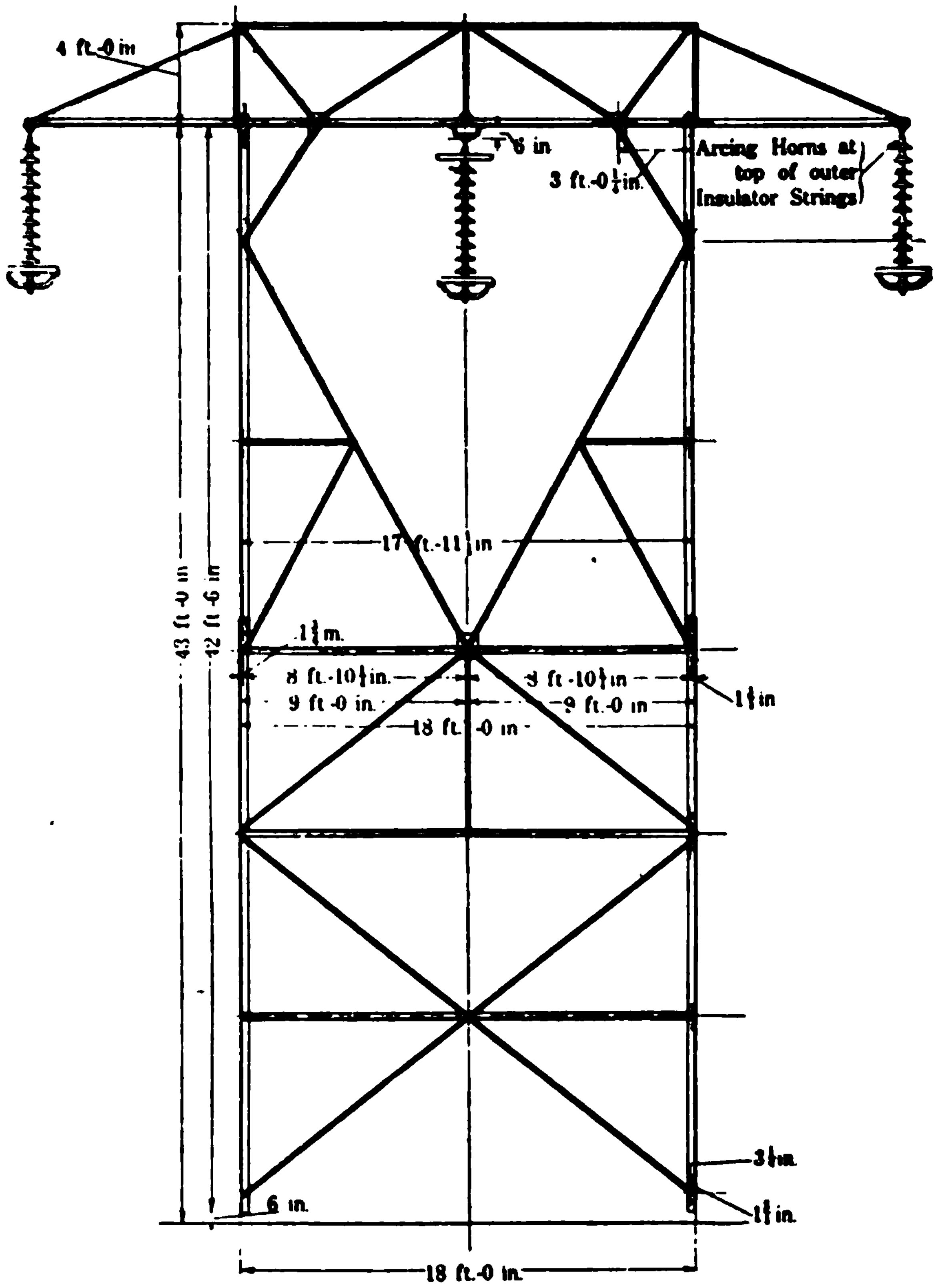

FIG. 1287.—Tower construction suspension insulators, guard rings, etc., of the Big Creek-Los Angeles 246-mile transmission at 220,000 volts. This is one of two duplicate transmission circuits.

This illustrates the arrangement for supporting the three wires of a three-phase system with the insulators and guard rings necessary to properly protect the 220,000-volt transmission. The wires themselves are nearly 1 inch in diameter, of stranded aluminum 750,000 c.m., with steel cores. They are spaced 17 feet 3 inches apart, and the towers vary in distance from each other from 600 to 2,900 feet, according to the locality. The conductors are pulled up to a uniform tension of 4,500 pounds.

Sub-Stations

At or near the point where electrical energy is to be utilized after its transmission, sub-stations must be arranged for reducing the voltage of transmission. With modern transformers the pressure can at once be reduced to any desired value. Pressures of 220,000 volts down to 66,000 volts are generally transformed to either 6,600 or 2,300 at the outskirts of cities. At this pressure the power is then carried into the cities and reduced as needed to 440, 220 and 110 volts.

Early sub-stations were always constructed in fireproof buildings which housed the entire equipment. The modern tendency is toward the use of outdoor sub-stations inasmuch as all equipment can be made waterproof and the cost of the building is unnecessary. An enclosure fenced with iron wire and protected at the top with barbed wire is considered sufficient to keep people away from dangerous apparatus. If the power is to be transformed from alternating to direct current, requiring the use of rotary converters, buildings will be required to house the equipment.

All early sub-stations, whether containing stationary apparatus or rotating apparatus, were manually operated. Connections between incoming and outgoing lines were established by switches operated by hand by a station attendant. In late years there has been an increasing tendency toward automatic sub-stations. Manually operated apparatus is justified only when an attendant is required for other duties or for fire and liability insurance. Even in such cases the automatic apparatus will effect economies in maintenance. The operation of manually and automatically operated stations is quite similar. The automatic station merely extends the control of the manual station to include the starting, paralleling and stopping of equipment. Automatic control responds either to a demand for power or to a master element which causes the equipment to be manipulated to meet the load requirements. With manually operated equipment the apparatus is shut down when load conditions permit. The automatically operated station functions in the same manner.

For railway purposes an automatic sub-station consists of a number of standard contactors and relays which, together with a motor-driven controller, perform the usual functions of starting up, operating and shutting down the sub-station entirely independent of manual control. If the trolley potential, normally

600 volts, falls to 450 or below, the sub-station automatically starts up. This is brought about through the medium of a contact-making voltmeter which closes the circuit necessary to start the drum controller in operation. The contact fingers and segments of this controller energize the operating coils of the alternating-current starting and running and field switches in proper order. When the machine reaches normal voltage, the direct-current line switch is closed and the controller comes to rest. The sub-station machine then continues to supply current until the demand falls below some predetermined value, at which time a current relay operates and shuts down the apparatus.

Power may be distributed within city limits either overhead or underground. There is an increasing tendency toward placing cables in conduits up to and including 26,000 volts. Such cables are now available with impregnated paper insulation which operate successfully practically indefinitely. Properly designed and installed underground systems are unquestionably less liable to derangement than overhead lines.

While it is impossible to predict what the ultimate developments in the generation and utilization of power will be, it seems reasonably certain that higher voltages will be the rule. With the perfection of transmission at higher voltages and the interlinking of the great power stations, it is not improbable that, in the near future, Boston, Washington, and the intervening cities along the Atlantic coast will be supplied from one great superpower system. Such a project has already been surveyed and declared to be feasible. With such a system which could utilize steam power at the mines or at tide-water and water power from rivers which are unsuitable for ordinary power purposes on account of seasonable variation of flow, it might be possible to materially lower the cost of the production of electrical energy as well as the investment in equipment. The conservation of the natural resources of the country by such systems is well worthy of serious and extended consideration.

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